Determination of Demands Resulting from High Mass, Low Velocity Debris Impact on Structures

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DETERMINATION OF DEMANDS RESULTING FROM HIGH MASS, LOW VELOCITY DEBRIS IMPACT ON STRUCTURES

by

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Presented to the Graduate and Research Committee of Lehigh University in Candidacy for the Degree of Doctor of Philosophy in Structural Engineering

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Contents

Acknowledgments............................................................................................................................... iv

List of Tables........................................................................................................................................ xi

List of Figures......................................................................................................................................... xii

Abstract................................................................................................................................................ 1

1. Introduction........................................................................................................................................ 3
   1.1. Background ............................................................................................................................... 3
   1.2. Research program objectives ......................................................................................................... 6
   1.3. Manuscript organization................................................................................................................ 7

2. Full-Scale Experimental Study of Axial Impact Demands Resulting from High Mass, Low Velocity Debris ......................................................................................................................... 9
   2.1. Introduction..................................................................................................................................... 9
   2.2. Equivalent one-dimensional elastic bar model................................................................................. 10
   2.3. Experimental program.................................................................................................................... 12
      2.3.1. Debris types............................................................................................................................. 13
      2.3.2. Material properties ................................................................................................................ 15
      2.3.3. Instrumentation....................................................................................................................... 16
      2.3.4. Test matrix............................................................................................................................. 17
   2.4. Experimental results....................................................................................................................... 19
      2.4.1. Wood pole test......................................................................................................................... 19
2.4.1.1. Effect of contact area ratio ................................................................. 19

2.4.1.2. Effect of inelastic response ................................................................. 22

2.4.1.3. Effect of contact stiffness ................................................................. 23

2.4.2. Steel tube and shipping container test .................................................. 26

2.4.2.1. Elastic response ................................................................................. 26

2.4.2.2. Inelastic response ............................................................................. 28

2.5. Discussion of results .................................................................................. 30

2.5.1. Impact force and duration estimation ................................................... 30

2.5.2. Response of the structural members ..................................................... 35

2.6. Conclusions ............................................................................................... 36

3. Estimation of Demands Resulting from Inelastic Axial Impact of Steel Debris ...... 38

3.1. Introduction ............................................................................................... 38

3.2. Equivalent one-dimensional inelastic bar model ........................................ 40

3.3. Experimental program .............................................................................. 44

3.4. Finite element modeling of debris impact ................................................ 45

3.4.1. Load cell finite element model ............................................................... 46

3.4.2. Steel tube finite element model ............................................................. 47

3.4.3. Shipping container finite element model ................................................. 47

3.5. Comparison of numerical and experimental results ................................... 50

3.6. Numerical simulation and discussion ...................................................... 54
3.6.1. Steel tube impact results ................................................................. 54

3.6.2. Shipping container impact results .................................................. 56

3.6.2.1. Shipping container peak impact force ....................................... 59

3.6.2.2. Shipping container impact duration .......................................... 60

3.7. Proposed impact demand estimation for inelastic axial debris impact.......... 61

3.7.1. Peak impact force estimation ......................................................... 62

3.7.2. Impact force-time history estimation ............................................. 64

3.8. Dynamic response of the structural members ..................................... 66

3.9. Conclusions ..................................................................................... 68

4. A Simplified Model for Estimating Axial Impact Forces Resulting from Elastic Debris with Nonstructural Mass ......................................................... 70

4.1. Introduction .................................................................................... 70

4.2. Simplified one-dimensional impact model ........................................ 71

4.3. Experimental program .................................................................... 76

4.4. Finite element modeling of steel tube impact ................................... 80

4.4.1. Numerical model ........................................................................ 80

4.4.2. Validation of numerical models .................................................. 81

4.5. Experimental and numerical results ................................................ 83

4.6. Impact force time history estimation .............................................. 87

4.7. Effect of nonlinearity on impact forces .......................................... 90
4.8. Conclusions ........................................................................................................... 94

5. Effect of Nonstructural Mass on Debris Impact Demands: Experimental and Simulation Studies 96

5.1. Introduction ............................................................................................................. 96

5.2. Simplified analytical impact model ......................................................................... 98

5.2.1. Primary pulse force estimation ............................................................................. 102

5.2.2. Secondary pulse force estimation ......................................................................... 102

5.3. Shipping container impact test ................................................................................ 104

5.3.1. Experimental program .......................................................................................... 104

5.3.2. Experimental results ............................................................................................ 107

5.4. Finite element modeling of container impact .......................................................... 110

5.4.1. Loaded container model ....................................................................................... 110

5.4.2. Validation of numerical models ........................................................................... 113

5.5. Numerical results and proposed impact demand estimation approach ................. 114

5.5.1. Parametric study .................................................................................................. 114

5.5.2. Simplified model for debris impact demand estimation ....................................... 115

5.5.3. Comparison of simulated and estimated results ................................................... 116

5.5.3.1. Case 1: sliding NSM ....................................................................................... 116

5.5.3.2. Case 2: tied NSM ............................................................................................ 120

5.5.3.3. Case 3: rigidly attached NSM ......................................................................... 123

viii
5.6. Discussion of results ........................................................................................................ 127
   5.6.1. Impact force-time history comparison ..................................................................... 127
   5.6.2. Dynamic response of the structural members ......................................................... 129

5.7. Conclusions .......................................................................................................................... 132

6. Study of Demands Resulting from Transverse Impact of Debris ...................................... 134
   6.1. Introduction ....................................................................................................................... 134
   6.2. Simplified models for transverse debris impact ............................................................ 134
   6.3. Test specimens and setup ............................................................................................... 137
   6.4. Experimental results ....................................................................................................... 140
      6.4.1. Transverse impact of shipping container members ................................................. 140
      6.4.2. Transverse impact of simplified members .............................................................. 143
   6.5. Transverse debris impact demands estimation ............................................................. 144
      6.5.1. Impact force-time history ........................................................................................ 146
      6.5.2. Peak impact force and impact duration ................................................................. 147
   6.6. Dynamic response of the structural members ............................................................... 148
   6.7. Conclusions ....................................................................................................................... 150

7. Summary and Conclusions ..................................................................................................... 151

References .................................................................................................................................. 153

Vita ............................................................................................................................................ 158
List of Tables

Table 2.1. Load cell details ........................................................................................................... 16
Table 2.2. Test matrix for wood pole series .................................................................................. 18
Table 2.3. Test matrix for shipping container series ..................................................................... 18
Table 2.4. Error of peak impact force of the proposed model....................................................... 31
Table 2.5. Error of impact duration of the proposed model............................................................ 31
Table 3.1. Parameters of the equivalent bilinear bar model for shipping container peak impact
          force estimation...................................................................................................................... 64
Table 4.1. Test matrix for elastic axial impact of steel tube with NSM ........................................... 79
Table 5.1. Test matrix for empty and loaded shipping container series ........................................ 107
Table 6.1. Test matrix for transverse debris impact ....................................................................... 138
Table 6.2. Equivalent mass and stiffness of the SDOF impact model for transverse debris impact
          estimations ........................................................................................................................... 146
List of Figures

Figure 1.1. Debris damage in Samoa (Photo: H.R. Riggs) ................................................................. 4

Figure 2.1. Structure debris impact model with contact region ......................................................... 10

Figure 2.2. Pendulum impact test setup .............................................................................................. 13

Figure 2.3. Debris section details and strain gauge locations .............................................................. 15

Figure 2.4. Peak impact force versus impact velocity for wood pole test series without contact material ......................................................................................................................... 20

Figure 2.5. Impact duration versus impact velocity for wood pole test series without contact material ......................................................................................................................... 21

Figure 2.6. Speed of sound versus impact velocity for elastic wood pole series .................................. 21

Figure 2.7. Undamaged (WT 8) and damaged (WT 9) section of the wood pole during inelastic trials .................................................................................................................................................. 22

Figure 2.8. Effects of contact materials on peak impact force .......................................................... 24

Figure 2.9. Effects of contact materials on impact duration .............................................................. 24

Figure 2.10. Impact force time histories for wood pole test series with contact materials: (a) rubber sheet at 1.5 m/s, and (b) plywood sheets at 1.2 m/s .............................................................................. 25

Figure 2.11. Impulse versus impact velocity for wood pole test series ............................................ 25

Figure 2.12. Measured peak impact force versus velocity for steel tube and shipping container elastic tests .......................................................................................................................................... 27

Figure 2.13. Measured impact duration versus velocity for steel tube and shipping container elastic tests .......................................................................................................................................... 27

Figure 2.14. Force and strain time histories for one of the trials from CT 5 ........................................ 28

Figure 2.15. Comparison of peak impact forces from elastic and inelastic shipping container
impact tests................................................................................................................................. 29

Figure 2.16. Comparison of impact duration from elastic and inelastic tests for shipping container
.................................................................................................................................................. 29

Figure 2.17. Shipping container damage: buckling of the bottom rail (CT 6), weld-line fracture
near the bottom corner fitting (CT 8), buckling of the corrugated top panel and local
buckling of the top rail (CT 9 & CT 10) .................................................................................... 30

Figure 2.18. Non-dimensionalized load cells histories for three types of debris: shipping container
(CT), wood pole (WT), and steel tube (Note: IR = impulse ratio) .............................................. 33

Figure 2.19. Non-dimensionalized measured values versus impact velocity for wood pole tests:
(a) peak impact force; and (b) impact duration ........................................................................... 34

Figure 2.20. Non-dimensionalized measured values versus impact velocity for shipping container
and steel tube tests: (a) peak impact force; and (b) impact duration ........................................... 35

Figure 2.21. Response spectra for debris axial impact forces of equal amplitude ....................... 36

Figure 3.1. Estimation of inelastic debris impact force using equivalent 1D bar model ............... 41

Figure 3.2. Full-scale shipping container test setup ........................................................................ 45

Figure 3.3. Steel tube and load cell mesh details and steel tube responses at 0.2 ms after impact
(Normalized Stress = von-Mises stress / yield stress) ................................................................. 47

Figure 3.4. (a) The shipping container model with structural details (wooden floor panel and west
side panel not shown). (b) Section details of the shipping container (units: cm) ......................... 49

Figure 3.5. Comparison of the numerical and experimental results during elastic impact of the
steel tube at 2.2 m/s: (a) strain-time histories, and (b) impact force-time histories .................... 51

Figure 3.6. Comparison of the force-time histories from shipping container elastic experiments
and FE simulations at 1.5 m/s ...................................................................................................... 53

Figure 3.7. Comparison of the force-time histories from shipping container inelastic experiments

xii
and FE simulations at 3.8 m/s ........................................................................................................53

Figure 3.8. Comparison of the numerical and experimental strain-time histories of the shipping container: (a) elastic impact at 1.5 m/s, and (b) inelastic impact at 3.8 m/s ..............................54

Figure 3.9. Estimated and measured peak impact force for steel tube debris (local buckling of EPH model at 14 m/s shown)........................................................................................................55

Figure 3.10. Measured and simulated shipping container damage due to axial impact..............57

Figure 3.11. Impact force-time histories of shipping container at 12 m/s....................................58

Figure 3.12. Impulse versus impact velocity for shipping container during inelastic axial impact58

Figure 3.13. Shipping container peak impact force generated at different velocities.................60

Figure 3.14. Impact duration for different axial impact cases of shipping container.....................61

Figure 3.15. Static force versus axial deformation for different cases of shipping container axial loading ........................................................................................................................................63

Figure 3.16. Nondimensionalized impact force-time histories for different inelastic axial impact cases of the shipping container ........................................................................................................65

Figure 3.17. Response spectra for shipping container inelastic axial impact forces of equal amplitude ......................................................................................................................................67

Figure 4.1. One-dimensional impact model of debris with nonstructural mass (NSM) ............72

Figure 4.2. Definition of stress wave ratios for different wave paths along the debris length.....73

Figure 4.3. Comparison of stress wave ratios for different cases of returning waves.................74

Figure 4.4. Idealized impact force-time history of debris with nonstructural mass using 1D model ........................................................................................................................................76

Figure 4.5. Experimental impact setup (units: cm)........................................................................79

Figure 4.6. Steel tube and load cell mesh details and steel tube responses at 0.3 ms after impact 81

Figure 4.7. Comparison of impact force-time histories from experiments and simulations for steel
tube with impact velocity of 2 m/s........................................................................................................82

Figure 4.8. Comparison of experimental data and simulation results for steel tube with 345% NSM at 2 m/s ........................................................................................................................................82

Figure 4.9. Effect of NSM on wave speed along the steel tube ..............................................................84

Figure 4.10. Peak impact force versus impact velocity for steel tube with full distribution of NSM ........................................................................................................................................84

Figure 4.11. Peak impact force versus impact velocity for steel tube with partial distribution of NSM (front half and back half) ........................................................................................................................................85

Figure 4.12. Impact duration versus impact velocity for steel tube with full distribution of NSM ........................................................................................................................................86

Figure 4.13. Impact duration versus impact velocity for steel tube with partial distribution of NSM ........................................................................................................................................86

Figure 4.14. Relationship between impulse and momentum for steel tube with fully and partially distributed NSM ........................................................................................................................................87

Figure 4.15. Nondimensionalized peak impact force versus impact velocity for steel tube tests and simulations ........................................................................................................................................88

Figure 4.16. Nondimensionalized impact duration versus impact velocity for steel tube tests and simulations ........................................................................................................................................89

Figure 4.17. Nondimensionalized impact force histories for the steel tube experiments and simulations and their comparison with the 1D model ........................................................................................................................................90

Figure 4.18. Impact force-time histories for inelastic axial impact of the steel tube without NSM ........................................................................................................................................92

Figure 4.19. Peak force versus impact velocity for inelastic impact of steel tube with and without NSM ........................................................................................................................................92

Figure 4.20. Impact duration versus impact velocity for inelastic impact of steel tube with and
Figure 4.21. Impulse versus impact velocity for inelastic impact of steel tube with and without NSM ................................................. ................................................... ........................................... 93

Figure 5.1. Estimation of debris impact force using equivalent 1D bar model......................... 100

Figure 5.2. Idealized force-time histories due to impact of debris using equivalent NSM-spring bar model ..................................................................................................... 104

Figure 5.3. Full-scale empty and loaded shipping container test setup .................................. 105

Figure 5.4. Shipping container payload: (a) water bladder (NSM case 1); (b) concrete panels with bracing system (NSM case 2) ................................................................................................ 106

Figure 5.5. Definition of the primary and secondary impulses and durations for a typical impact force history ........................................................................................................... 108

Figure 5.6. Measured impact force-time histories for empty and loaded container test series at 1.0 m/s ......................................................................................................................... 108

Figure 5.7. Measured primary peak impact force versus impact velocity for loaded and empty shipping container test series ................................................................. 109

Figure 5.8. Measured primary impact duration versus impact velocity for loaded and empty shipping container test series ................................................................. 109

Figure 5.9. Measured impulse for empty and loaded shipping container test series (solid symbols: $I_t$ = total impulse, hollow symbols: $I_p$ = primary impulse) ........................................... 110

Figure 5.10. Finite element model of shipping container: (a) structural framework; (b) configuration of lumped mass for loaded container (side panel is removed) ................. 112

Figure 5.11. Comparisons of impact force-time histories from loaded shipping container experiment T3C1 and FE simulation at 1.4 m/s ......................................................... 113

Figure 5.12. Comparisons of impact force-time histories from loaded shipping container
Figure 5.13. Primary peak impact force generated from one bottom and two bottom corner impact of the half loaded and fully loaded shipping container with NSM case 1

Figure 5.14. Impact duration for the half loaded and fully loaded shipping container with NSM case 1: (a) primary impact duration; (b) total impact duration

Figure 5.15. Impulse for the half loaded and fully loaded shipping container with NSM case 1: (a) primary impulse; (b) total impulse

Figure 5.16. Primary peak impact force generated from one bottom and two bottom corner impact of the loaded shipping container with NSM case 2

Figure 5.17. Primary and total impact duration for loaded shipping container with NSM case 2

Figure 5.18. Impulse for loaded shipping container with NSM case 2 (solid symbols: $I_t =$ total impulse; hollow symbols: $I_p =$ primary impulse)

Figure 5.19. Peak impact force from empty and loaded shipping container with NSM case 3 at different velocities

Figure 5.20. Impact duration for empty and loaded shipping container with NSM case 3 at different impact velocities

Figure 5.21. Impulse versus impact velocity for empty and loaded shipping container with NSM case 3

Figure 5.22. Nondimensional impact force-time histories for elastic and inelastic axial impact of the loaded shipping container with NSM cases 1, 2 and 3

Figure 5.23. Response spectra for fully loaded shipping container impact forces of equal amplitude (NSM case 1)

Figure 5.24. Response spectra for 8% loaded shipping container impact forces of equal amplitude (NSM case 2)
Figure 5.25. Response spectra for half-loaded shipping container impact forces of equal amplitude (NSM case 3) ................................................................. 132

Figure 6.1. SDOF impact model for transverse impact of elastic debris ........................................... 137

Figure 6.2. Transverse debris impact test setup .............................................................................. 139

Figure 6.3. Section details of shipping container components and simplified transverse members (units: cm) ........................................................................................................ 139

Figure 6.4. Inelastic damage due to transverse impact: hollow tube section (H2), solid bar section (S2), container bottom beam (C3), container corner post (C4). Dashed lines represent the undamaged position of members ............................................................................. 140

Figure 6.5. Measured force-time histories for shipping container with impact velocities of approximately 1 m/s and 4 m/s for elastic and inelastic impact, respectively .................. 141

Figure 6.6. Measured shipping container peak impact force due to axial and transverse impact 142

Figure 6.7. Measured impact duration of shipping container resulting from axial and transverse impact .................................................................................................................. 142

Figure 6.8. Peak impact force versus impact velocity for impact of simplified transverse members .................................................................................................................. 143

Figure 6.9. Impact duration versus impact velocity for impact of simplified transverse members .................................................................................................................. 144

Figure 6.10. Approximation of effective mass for transverse member with lumped masses at the ends .................................................................................................................. 145

Figure 6.11. Nondimensional load cells histories resulting from transverse impact: (a) shipping container bottom beam; (b) shipping container corner post; (c) hollow tube section; (d) solid bar section .................................................................................................. 147

Figure 6.12. Nondimensionalized measured peak impact force and impact duration versus impact velocity
velocity for transverse shipping container impact tests ...................................................... 147

Figure 6.13. Nondimensionalized measured peak impact force and impact duration versus impact
velocity for transverse impact of simplified members ....................................................... 148

Figure 6.14. Response spectra for transverse shipping container impact forces of equal amplitude
............................................................................................................................................... 150
Abstract

Impact of debris generated during extreme events such as floods, tsunamis, and hurricane storm surge and waves can cause severe structural damage. It is necessary to be able to estimate debris impact forces properly in order to design the structures to resist typical water-borne debris. The objective of this study is to characterize the impact demands generated during debris impact on structures and to develop a model that can estimate impact force and duration accurately.

To quantify the forces generated during transverse and axial debris impact an experimental study was conducted on a full-scale wood utility pole, steel tube, solid bar, and standard shipping container subjected to in-air impacts. Effect of nonstructural mass on debris impact demands was assessed by considering payload for shipping containers. A nonlinear dynamic finite element model of a standard shipping container including contents is developed and validated by comparing with the full-scale impact experiments. Parametric studies are carried out to investigate the effects of impact velocity, nonstructural mass attachment, and magnitude of payload mass during both elastic and inelastic axial impact of a shipping container.

Simplified analytical models are developed and validated with data from full-scale impact experiments and simulated results. The simplified models are found to provide an accurate estimate of debris impact demands. The results show that impact forces estimated by current design guidelines are not accurate and can lead to over or under prediction of the design force levels. The models presented in this dissertation are
developed for use in design guidelines to define debris impact forces and durations for design.
CHAPTER 1

Introduction

1.1. Background

Tsunamis, hurricane storm surges, and floods generate water-borne debris such as shipping containers, vehicles, boats, lumber and utility poles. Severe damage to residential and commercial buildings, vertical evacuation shelters, and port and industrial facilities in the inundation zones due to debris impact forces during such events have been reported (Robertson et al. 2010, 2012, 2007; Naito et al. 2013; Fraser et al. 2013; Chock et al. 2011). The impact force induced by the floating debris is not well understood. The accurate estimation of the impact force demands from debris strikes is needed to enhance the performance of the structural elements during such events.

Site surveys demonstrated that any floating or mobile object in the nearshore/onshore areas can become floating debris during the hurricane storm surge and tsunami inundation, and therefore may cause substantial loads on structures. This includes large debris such as barges (Robertson et al. 2007). Tsunami reconnaissance surveys have indicated that objects such as large boats and vessels can become adrift by the tsunami flow due to the failure of mooring systems and therefore could become a serious hazard to coastal buildings (Naito et al. 2013). The failed building components themselves, including steel, concrete, and wood structural components, become part of the debris field and contribute to impact events (Robertson et al. 2010; Chock et al. 2011). Standard
shipping containers are ubiquitous and therefore are considered a common debris-type in many coastal regions and can result in considerable dispersal and high likelihood of impact to structures (Naito et al. 2013). Severe damage to steel and reinforced concrete structural members due to shipping container impact has been observed (Robertson et al. 2012, 2007). Figure 1.1 shows impact damage from a shipping container in a small village in American Samoa during the 2009 Samoan Tsunami (Robertson et al. 2010).

![Image of debris damage in Samoa]

**Figure 1.1.** Debris damage in Samoa (Photo: H.R. Riggs)

Relatively little research has been devoted to water-borne debris, although recent tsunamis have illustrated the potential for structural damage from such debris. In previous studies maximum impact forces from flood-borne woody debris were experimentally investigated and empirical formulae were proposed (Haehnel and Daly 2002, 2004; Matsutomi 2009). Related to vessel ‘debris’ impact, experimental and numerical studies have been conducted to define the barge impact force during barge collision with bridge piers (Consolazio et al. 2005, 2006, 2009; Sha and Hao 2012, 2013). Numerical investigations have been carried out to evaluate the generated forces during shipping
container impact on a reinforced concrete column (Madurapperuma and Wijeyewickrema 2013). A small-scale model of the shipping container was tested in a wave flume to investigate the effect of water on debris impact forces (Riggs et al. 2013; Ko 2013; Yeom et al. 2009). The contribution of water to the debris impact demands was found to be secondary to the “pure” structural impact. In FEMA P646 (2012), for a 20-ft shipping container axial impact it is suggested to increase the peak force by 14% to account for the “hydrodynamic mass” effect of the fluid.

Despite its importance, there is no consensus how to define design impact forces. Debris impact is covered in several codes and design standards. Current design guidelines (ASCE 7 2010; FEMA P55 2011; FEMA P646 2012) use simple approaches to estimate water-borne debris impact forces, but there is no consensus on the specification of the design force (Piran Aghl et al. 2013). Two approaches are used to estimate the peak impact forces in U.S. design guidelines: impulse-momentum and contact stiffness. The impulse-momentum approach equates the momentum of the debris with the force impulse and the contact stiffness approach is based on a single-degree-of-freedom spring-mass system where the stiffness of the interaction between the debris and the structure is required (Haehnel and Daly 2004). Eq. (1.1) presents the peak impact force formula in ASCE 7-10 (2010), which is based on the impulse-momentum approach and the assumption of half-sine pulse force.

\[ F = \frac{\pi m v}{2 \Delta t} \]
in which \( m \) is the total mass of the debris, \( v \) is the impact velocity, and \( \Delta t \) is the time to reduce the debris velocity to zero. Based on Haehnel and Daly (2004), FEMA P646 (2012) specifies a peak impact force given in Eq. (1.2), using the contact stiffness approach in which \( k \) is the effective contact stiffness of the debris and structure.

\[
F = \sqrt{\frac{m}{k}} v \tag{1.2}
\]

The proper determination of \( \Delta t \) and \( k \) values is necessary to provide an accurate estimation of the peak impact force using impulse-momentum and contact stiffness approaches, respectively.

### 1.2. Research program objectives

The objective of this research project is to improve our understanding of, and predictive capabilities for, water-borne debris impact forces on structures. It is necessary to be able to quantify accurately the debris impact forces generated by tsunami events. The forces generated from debris impact of structures, for example evacuation shelters and critical port facilities such as fuel storage tanks, are currently not accurate. Debris impact forces specified by current codes and standards are based on rigid body dynamics. However, tsunami debris such as shipping containers are unlikely to be rigid compared to the walls, columns and other structures that they impact.

A full-scale experimental program is developed to obtain a rich set of experimental data in order to assess the behavior of low speed, high mass debris impact on structures. These results are used to calibrate debris impact simulation models.
The specific aim of this dissertation is to develop simplified models to estimate the demands resulting from flexible debris impact. The results of this study have the potential to improve the specification of design forces for debris in codes and standards.

1.3. Manuscript organization

In Chapter 2, an elastic debris impact model is described to present the estimation methods for an axial debris impact. The elastic and inelastic experimental results for three types of debris are presented. This is followed by a comparison between the experimental results and the estimated results from the proposed model.

In Chapter 3, the results of impact demands from nonlinear dynamic finite element (FE) simulation of simplified and complex debris-type models are presented. The FE models are validated by comparing computed responses with the results from full-scale in-air debris impact experiments. A one-dimensional bar model is developed, illustrated, and validated to estimate the debris impact demands under inelastic response.

In Chapter 4, the experimental results of the in-air axial impact tests on a component of a shipping container with rigidly attached NSM are presented. The results are used to validate nonlinear dynamic FE model that are extended for parametric evaluation. A simplified impact model is developed and validated by the experimental and simulation results to estimate the impact demands from debris with non-uniform NSM.

In Chapter 5, the effect of NSM during elastic and inelastic axial impact of debris is evaluated. The results of full-scale in-air axial impact tests conducted on a loaded
shipping container are presented. FE models of the container with the contents are developed and validated. A simplified design-level model is developed to estimate the impact demands from debris with included NSM and is validated by the experimental and simulation results.

In Chapter 6, an elastic debris impact model is developed to estimate transverse debris impact demands. The elastic and inelastic experimental results for transverse shipping container impact are presented. The experimental results and the estimated results from the proposed model are compared. The results are also compared with the estimated values form existing design guidelines.

Finally, Chapter 7 presents summary of the conducted research and concluding remarks drawn based on the experimental, simulation and analytical work performed in this study.
CHAPTER 2

Full-Scale Experimental Study of Axial Impact Demands Resulting from High Mass, Low Velocity Debris

2.1. Introduction

Tsunamis can generate a considerable amount of flow velocity on land. The associated hydrodynamic effects coupled with the plethora of unrestrained objects and frangible structures produce significant debris that can travel similar velocities as the flow. Design of structures to resist the tsunami-driven debris requires a conservative estimation of the forces generated at impact. Limited experimental data on debris impact demands exist. Current design guidelines (ASCE 2010; FEMA 2012; CCM 2011) use simple approaches for debris impact force but there is no consensus on the definition of design impact force (Piran Aghl et al. 2013).

This chapter presents an experimental program in which full-scale in-air axial impact tests were carried out with a wood utility pole, steel tube and shipping container. The main objective was to develop a simple model to estimate the peak force and duration during debris axial impact events. The experimental data were used to validate the proposed model (Riggs et al. 2013).
2.2. Equivalent one-dimensional elastic bar model

A simplified dynamic model is used to provide an accurate estimate of the impact demands. The debris is modeled as a uniform elastic bar of length $L_d$ and mass $m_d$, and it is subjected to axial impact (Paczkowski et al. 2012). A schematic of the debris impacting the structural member is shown in Figure 2.1. $k_s$ and $m_s$ are the structural stiffness and mass, respectively. For the experimental program, the structure was considered rigid ($k_s \to \infty$). A spring with stiffness $k_c$ represents the local stiffness of the contact region between the debris and structure. This contact stiffness is associated with non-structural coverings on the structural component or debris (i.e., contact materials) and imperfections in the contact region. The contact stiffness is conservatively taken as $\infty$ in the model. The effect of contact stiffness ($k_c$) on impact force and duration was examined in the wood pole experimental tests. To apply the model to debris, such as a shipping container, an equivalent 1D bar is defined that has a total mass of the debris $m_d$; $L_d$ is the length of the axial impacting member of the debris; $E$ is its modulus of elasticity; and $A_d$ is the cross sectional area of the axial member(s) of the debris that are subjected to the impact. The stiffness of the equivalent 1D bar (i.e., equivalent stiffness) is

$$k_d = \frac{EA_d}{L_d}$$

(2.1)

![Figure 2.1. Structure debris impact model with contact region](image-url)
The impact force for the elastic bar model of Paczkowski et al. (2012) is obtained from the solution of the one-dimensional wave equation. This formulation assumes that the projectile impacts a rigid structure (i.e., $k_s$ and $k_c \to \infty$) and responds in a uniaxial mode. The result provides a simple expression for the impact force:

$$F = v_i \sqrt{k_d m_d}$$

in which, $F$ is the peak impact force and $v_i$ is the impact velocity. Note that the quantity in the radical can also be expressed as $E \rho A_d^2$, where $\rho = m_d / A_d L_d$. Eq. (2.2) is convenient for computation, but the alternative form emphasizes that the length of the projectile, or its total mass, does not control the impact force. Therefore, the impact force in this model does not depend on the total momentum. This was demonstrated in the experiments of Paczkowski et al. (2012).

Eq. (2.2) also can be derived using conservation of energy applied to a single degree-of-freedom system with stiffness $k_d$ and mass $m_d$, i.e., all the mass is lumped at the end of the bar (Haehnel and Daly 2002, 2004). The energy method equates the initial kinetic energy of the debris with the potential energy during deformation of the bar.

The solution of the one-dimensional wave equation results in a constant value of impact force during the entire duration (i.e. rectangular pulse force), based on stress wave propagation through the bar. The duration is defined here as the time between the initial contact of the debris with the structure and the end of the contact (i.e., when impact force becomes zero). Because elastic impact is assumed, i.e., the coefficient of restitution $e = 1$, the duration is given by
\[ t_d = \frac{(1 + e)v_l m_d}{F} = 2 \sqrt{\frac{m_d}{k_d}} \quad (2.3) \]

This result is clearly evident from an impulse-momentum approach, in which the rectangular pulse obtained from the wave-equation solution is adopted. Note that this is not the same duration as would be calculated based on the single degree-of-freedom model.

### 2.3. Experimental program

Full-scale experiments were conducted on three different types of debris to investigate the generated impact force and duration. Impact demands due to air-borne debris is thought to differ from water-borne debris due to the absence of the “hydrodynamic mass” effect of the fluid behind the debris (FEMA 2012). The contribution of water to the impact demands was assessed through in-water testing of debris and was found to be secondary to the ‘pure’ structural impact (Riggs et al. 2013). Consequently, all test presented involve in-air axial impact of debris against load cells.

The impact was generated using a pendulum system as illustrated in Figure 2.2. The debris was suspended from 6.7 m long and 32 mm diameter steel cables with a low friction clevis assembly on each end. A winch system was used to pull back the debris to the desired height and a quick release allowed for a smooth disconnect. A predetermined impact velocity was generated by raising the debris to the desired height prior to release. The load cells were mounted on steel wide flange cross-beams and attached to vertical
members of the grillage. For each test series the location of the load cells were adjusted to ensure axial impact of the debris along the center of the load cell(s). The mass and stiffness of the cross-beams and frame were more than one order of magnitude greater than the specimen and load cells, thus minimizing dynamic interaction between the impact event and the frame response. Additionally, dynamic analysis of the grillage subjected to the measured impact forces time histories at the location of the load cells revealed that the displacement of the grillage during debris impact duration is negligible. Based on these results the grillage can be assumed to act as a rigid structure in response to the debris impact.

![Figure 2.2. Pendulum impact test setup](image)

2.3.1. Debris types

The three debris types are included in the research program: a 6.0 m wood utility pole; a 6.1 m steel tube; and an International Organization for Standardization (ISO) shipping
container measuring 6.0 m long, 2.4 m wide, and 2.6 m high. The wood utility pole represents a common debris type generated during tsunami, flood, and storm surge events (ASCE 2010). A 6.0 m (19.7 ft) wood utility pole with an average diameter of 24.2 cm was chosen to accommodate the experimental setup. The 6.0 m ISO container is also a common debris type in coastal port regions and due to its construction is buoyant and likely to disperse and impact structures during tsunamis. A steel tube with approximately the same cross-sectional area as the longitudinal members of the shipping container was included as a debris-type to better understand the impact characteristics of the structural members of the shipping container.

The wood utility pole was a standard Pennsylvania Power and Light pole that had been removed from service. The pole varies approximately linearly in diameter from the large end to the small end. The cross section of the wood pole at both ends is shown in Figure 2.3. The shipping container examined is a standard ISO 1CC type steel dry cargo container. The container has a specified total mass of 2300 kg and a maximum allowable gross mass of 30480 kg. The container is fabricated from four vertical corner columns, eight corner fittings, four longitudinal members made up of two top side rails and two bottom side rails, corrugated steel sides and a plywood floor with steel cross-beams. Details on the dimensions of the container are shown in Figure 2.3. The steel tube consists of a standard AISC rectangular HSS 64 × 38 × 4.8 (2.5 × 1.5 × 3/16 in.). The section was chosen to have a comparable cross-sectional area to that of the top side rail of the container. Images of the debris are included in Figure 2.2 and sectional details are summarized in Figure 2.3.
2.3.2. Material properties

The creosote treated, southern pine utility pole had a measured mass of 204 kg and a density of 748 kg/m$^3$. The published value for modulus of elasticity, 7584 MPa (SPIB 2012) for southern pine is used herein. Static tests for compression parallel to grain (ASTM D198 2014) were performed to determine the crushing strength of the wood pole. Three specimens of the wood pole were tested and the average measured value of crushing strength (i.e., compression strength) was 37 MPa (5.4 ksi). The mass of the steel tube was 39 kg and the total mass of the instrumentation installed on the tube was 4.5 kg. The modulus of elasticity and yield strength of the steel tube are taken to be 200 GPa and 315 MPa (ASTM 2010), respectively. The main members of the shipping container, including the top and bottom side rails, are made of steel Corten A. A tension coupon test was performed to determine the material properties of the axial members of the container;
the average value of yield strength and tensile strength were 381 MPa and 519 MPa, respectively, and the elastic modulus was measured to be 207 GPa.

### 2.3.3. Instrumentation

In order to provide sufficient resolution to capture accurately an impact event, data from all instrumentation (i.e., load cells, accelerometers, strain gauges, light sensors and displacement sensors) were recorded at 50 kHz. Table 2.1 lists three types of strain-based load cells, which were attached to the grillage. The grillage represented an essentially rigid structural component. To verify the measured impact force at the load cell and to assess stress wave propagation in the debris, strain sensors were used, as shown in Figure 2.3. In order to have a smooth contact between container and load cells, four 13 cm × 11 cm × 1.3 cm plates were welded to the corner fittings of the container, as shown in Fig. 2.

<table>
<thead>
<tr>
<th>Load cell</th>
<th>Impact area (cm²)</th>
<th>Natural period (ms)</th>
<th>Axial Stiffness (×10⁶ kN/m)</th>
<th>Capacity</th>
<th>Debris type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type A</td>
<td>113.2</td>
<td>0.333</td>
<td>2.92</td>
<td>222 kN (50 kips)</td>
<td>W</td>
</tr>
<tr>
<td>Type B</td>
<td>232.3</td>
<td>0.175</td>
<td>2.26</td>
<td>400 kN (90 kips)</td>
<td>W</td>
</tr>
<tr>
<td>Type C</td>
<td>64.2</td>
<td>0.031</td>
<td>52.54</td>
<td>1334 kN (300 kips)</td>
<td>W, S and C</td>
</tr>
</tbody>
</table>

Note: W = Wood pole; S = Steel tube; C = Container.

After raising the debris to the desired height and releasing it, the impact velocity was determined at the time of first contact between debris and load cell by two different methods: 1) using accelerometer and light sensors, and 2) using two optical displacement sensors. The impact velocities for the wood pole and steel tube test series were measured using Method 1. In this method, a slotted aluminum fin with perforations at a 1.27 cm (0.5 in.) spacing was attached under the debris (see steel tube in Figure 2.2). The
activation/deactivation of the light sensor was used to determine the time it takes to travel past each 1.27 cm perforation thus allowing for calculation of the average velocity at impact. The fin was placed to allow for determination of velocity immediately prior to impact. The acceleration was also measured during the same time using accelerometers. The measured average velocity over the last slot and the acceleration averaged over the same time period were used to compute the velocity at impact (assuming constant acceleration). Impact velocity for the shipping container was determined with Method 2. In this method, the displacement of the left and right side of the container at a height of 43 cm from the bottom of the container was measured as a function of time and averaged to determine the impact velocity of the shipping container. Comparison of calculated impact velocities from these two methods, for a number of trials on shipping container, resulted in an error of ±1%. The rebound velocity was measured using the same procedures.

2.3.4. Test matrix

The wood pole test series consisted of impacts to the large and small end of the pole. The effect of the impact area on the peak force and duration was assessed. A contact area ratio \((\alpha_c)\) defined as the ratio of impact area (i.e., contact surface between debris and target) to cross sectional area of the wood pole (small or large end) was used for the assessment. The value of \(\alpha_c\) for the load cells varied from 0.17 to 0.63. A steel plate with a thickness of 6.3 cm was bolted to the load cell type A to increase the \(\alpha_c\) to 0.91. In addition, the effect of contact stiffness was studied by adding different materials between the debris and load cell: a 2.5 cm thick rubber sheet was used in WT 3 and WT 6 test
series, and one to three, 1.6 cm thick plywood sheets were used in WT 5 test series. Table 2.2 summarizes the test matrix for the wood pole series.

**Table 2.2. Test matrix for wood pole series**

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Load cell type</th>
<th>Contact region material</th>
<th>Contact area ratio ($\alpha_c$)</th>
<th>Wood pole face</th>
<th>Debris response</th>
<th>Speed range (m/s)</th>
<th>No. of trials</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT 1</td>
<td>A</td>
<td>Steel plate</td>
<td>Large</td>
<td>0.91</td>
<td>Elastic</td>
<td>0.33-1.87</td>
<td>19</td>
</tr>
<tr>
<td>WT 2</td>
<td>A</td>
<td>N/A</td>
<td>Large</td>
<td>0.20</td>
<td>Elastic</td>
<td>0.52-1.69</td>
<td>17</td>
</tr>
<tr>
<td>WT 3</td>
<td>A</td>
<td>Rubber sheet</td>
<td>Large</td>
<td>0.20</td>
<td>Elastic</td>
<td>1.01-2.60</td>
<td>4</td>
</tr>
<tr>
<td>WT 4</td>
<td>A</td>
<td>N/A</td>
<td>Small</td>
<td>0.31</td>
<td>Elastic</td>
<td>0.27-1.77</td>
<td>7</td>
</tr>
<tr>
<td>WT 5</td>
<td>A</td>
<td>Plywood</td>
<td>Small</td>
<td>0.31</td>
<td>Elastic</td>
<td>1.24-1.30</td>
<td>5</td>
</tr>
<tr>
<td>WT 6</td>
<td>B</td>
<td>Rubber sheet</td>
<td>Small</td>
<td>0.63</td>
<td>Elastic</td>
<td>1.52-3.07</td>
<td>3</td>
</tr>
<tr>
<td>WT 7</td>
<td>B</td>
<td>N/A</td>
<td>Small</td>
<td>0.63</td>
<td>Elastic</td>
<td>1.30-2.92</td>
<td>12</td>
</tr>
<tr>
<td>WT 8</td>
<td>C</td>
<td>N/A</td>
<td>Small</td>
<td>0.17</td>
<td>Inelastic</td>
<td>1.20-3.07</td>
<td>10</td>
</tr>
<tr>
<td>WT 9</td>
<td>C</td>
<td>N/A</td>
<td>Small</td>
<td>0.17</td>
<td>Damaged</td>
<td>0.92-3.50</td>
<td>15</td>
</tr>
</tbody>
</table>

Load cell type C was used to measure the impact force for both steel tube and container test series. Elastic response of the steel tube was examined through 17 trials at impact velocities ranging from 0.16 m/s to 2.76 m/s. Five series of head-on impacts of the empty shipping container are presented: they include impacts to the four corners, three corners, two top corners, one top corner, and two bottom corners of the shipping container. The impact velocity for each series was increased up to yield of the axial member of the container. Two impact trials with high impact velocity were performed to investigate the inelastic behavior of the shipping container during head-on impact. The damaged container was also tested and results are compared with the undamaged elastic container response. The test matrix for the shipping container is given in Table 2.3.

**Table 2.3. Test matrix for shipping container series**

18
<table>
<thead>
<tr>
<th>Test No.</th>
<th>Load cell(s) position</th>
<th>Debris response</th>
<th>Impact velocity range (m/s)</th>
<th>No. of trials</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT 1</td>
<td>WT, ET, WB, EB</td>
<td>Elastic</td>
<td>0.43-2.42</td>
<td>10</td>
</tr>
<tr>
<td>CT 2</td>
<td>WT, ET, WB</td>
<td>Elastic</td>
<td>1.06-1.96</td>
<td>6</td>
</tr>
<tr>
<td>CT 3</td>
<td>WT, ET</td>
<td>Elastic</td>
<td>0.52-1.73</td>
<td>9</td>
</tr>
<tr>
<td>CT 4</td>
<td>WT</td>
<td>Elastic</td>
<td>0.36-1.52</td>
<td>14</td>
</tr>
<tr>
<td>CT 5</td>
<td>WB, EB</td>
<td>Elastic</td>
<td>0.42-2.26</td>
<td>18</td>
</tr>
<tr>
<td>CT 6</td>
<td>WB, EB</td>
<td>Inelastic (undamaged)</td>
<td>3.82</td>
<td>1</td>
</tr>
<tr>
<td>CT 7</td>
<td>WB, EB</td>
<td>Inelastic (damaged)</td>
<td>0.77-1.42</td>
<td>4</td>
</tr>
<tr>
<td>CT 8</td>
<td>WB</td>
<td>Inelastic (damaged)</td>
<td>0.75-2.75</td>
<td>14</td>
</tr>
<tr>
<td>CT 9</td>
<td>WT</td>
<td>Inelastic (undamaged)</td>
<td>3.76</td>
<td>1</td>
</tr>
<tr>
<td>CT 10</td>
<td>WT</td>
<td>Inelastic (damaged)</td>
<td>0.55-2.86</td>
<td>8</td>
</tr>
</tbody>
</table>

Note: W = West; E = East; T = Top; B = Bottom.

2.4. Experimental results

A total of 194 trials were conducted for the experimental program (92 wood pole, 17 steel tube, and 85 shipping container trials). For each trial, impact velocity, force and duration from the load cell(s), and strain of the debris were measured. Impact force is determined from the measured response of the load cell(s). The first natural period of the load cell was well below the impact durations. A comparison of the natural period of the load cells and the impact durations revealed that the impact force was accurately represented by the load cell reading.

2.4.1. Wood pole test

2.4.1.1. Effect of contact area ratio

The relationship between peak impact force and impact velocity for the wood pole series without supplemental contact material is presented in Figure 2.4. Results show that impact force varies linearly with velocity for all elastic impacts. Moreover, a comparison
of the results from varying contact area ratio ($\alpha_c$) from 0.17 to 0.91 indicates that the peak impact force does not depend on the impact contact area.

Figure 2.4. Peak impact force versus impact velocity for wood pole test series without contact material

Figure 2.5 displays the relationship between impact duration and impact velocity during elastic and inelastic impact of the wood pole. Test results for elastic cases show that the duration tends to decrease with increase in the impact velocity. The reduction in duration is due to the increase in speed of sound through the wood (i.e., stress wave propagation speed). The speed of sound was computed from the surface mounted strain gauges at two cross sections along the wood specimen: the difference in the stress wave arrival time between the strain gauges divided by the distance between two cross sections. As impact velocity increases, the speed of sound increased (see Figure 2.6). This is because the wood specimen is sensitive to the rate of loading (i.e., strain rate sensitive).
Figure 2.5. Impact duration versus impact velocity for wood pole test series without contact material

Figure 2.6. Speed of sound versus impact velocity for elastic wood pole series
2.4.1.2. Effect of inelastic response

To examine the effect of inelastic response of the wood debris, the contact area was decreased and impact velocity was increased for the WT 8 and WT 9 test series. Prior to WT 8 the pole contained a number of lengthways separations (i.e., checks) that remained stable during the preceding test series (see Figure 2.7). The WT 8 test series resulted in crushing of the contact surface and formation of shake-like damage outside of the contact zone. WT 9 exacerbated this damage. The end sections are illustrated in Figure 2.7 for comparison. The results of the test series are summarized in Figures 2.4 and 2.5. The maximum impact force for the undamaged wood pole with a contact area of 64.2 cm² (WT 8) was 296 kN corresponding to a 3.07 m/s impact velocity. This value is consistent with the estimated maximum compression strength of southern pine, which corresponds to 240 kN for the impact area used in WT 8. Following the damage generated in WT 8, the WT 9 test series was conducted to look at the residual effects on impact force and duration. Data from the WT 9 test series indicates that the damage reduced the elastic impact force demands by 18% and the maximum impact force decreased by 24% in comparison to WT 8. Impact duration increases noticeably as a result of the damage as shown for WT 8 and WT 9 in Figure 2.5.

Figure 2.7. Undamaged (WT 8) and damaged (WT 9) sections of the pole during inelastic trials
2.4.1.3. **Effect of contact stiffness**

The results of the test series with contact materials indicate that the peak impact force decreases with reduced contact stiffness. Figure 2.8 gives the relationship between impact force and velocity for the wood pole impacts with different contact materials. The results are compared with the best fit line obtained from elastic tests without contact material. The results show that the steel plate in the contact region does not change the peak force since the contact stiffness for this case was very high. The contact area for WT 3 test series was lower than WT 6 test series (see Table 2.2), resulting in lower contact stiffness of the rubber sheet and therefore higher reduction in peak impact force. The peak force from WT 3 and WT 6 test series decreases by 60% and 55%, respectively. Additionally, adding one to three plywood sheets in the contact region (WT 5) resulted in 18% to 27% reduction of the peak force. Adding more plywood sheets leads to a reduction in contact stiffness and this in turn reduces the peak force.

Effect of contact stiffness on impact duration is shown in Figure 2.9. The results show that the impact duration increases with reduced contact stiffness. The highest impact durations were associated with the lowest contact stiffness, which is WT 3 with $\alpha_c = 0.2$. During WT 5 test series, the contact stiffness decreases as the number of plywood sheets increases from 1 to 3, contributing to impact durations of 128% to 150% of that achieved from no contact material, respectively.
The net increase in impact duration and decrease in impact force resulting from reduced contact stiffness results in no net change in the impulse imparted for the wood pole series. This is illustrated in Figure 2.10, which compares the force time histories and impulse for elastic impacts with various contact materials at two impact velocities. The impulse is defined as the area under the force-time history over the defined impact
duration. The relationship between impulse and impact velocity with and without contact material is shown in Figure 2.11. The plywood material results in no significant change in impulse; the rubber material (WT 3 and WT 6 test series) resulted in a nominal decrease of 3.5% and 11% in impulse. Moreover, the impulse values for inelastic test series are compared with the elastic tests, as shown in Figure 2.11. The results show that the inelastic response of the damaged wood pole (WT 9) leads to a significant reduction in impulse for the higher impact velocities.

Figure 2.10. Impact force time histories for wood pole test series with contact materials: (a) rubber sheet at 1.5 m/s, and (b) plywood sheets at 1.2 m/s

Figure 2.11. Impulse versus impact velocity for wood pole test series
2.4.2. Steel tube and shipping container test

2.4.2.1. Elastic response

Impact force varies linearly with impact velocity for the shipping container and steel tube elastic test series, as shown in Figure 2.12. The peak impact force for the cases of multi-corner impact was obtained from the summation of the force-time history curves of the impacted load cells. The impact was considered perfect when the container hit all load cells at the same time. Due to the unrestrained swing of the container during the tests, most trials resulted in non-uniform impact of the load cells. The average force duration of the impacted load cells was used to define the impact duration of each trial. Figure 2.13 shows that impact durations remain constant over the range of impact velocities. The elastic shipping container test results show that a reduction in total impact area by reducing number of load cells (i.e., number of impact corners of the shipping container) leads to an increase in duration and a decrease in peak impact force. Therefore, the single corner impact of the container (CT 4) results in the highest duration and lowest peak force.

A comparison between the load cell reading and data from mounted strain gauges on the debris indicates that the force time history is not influenced by the dynamics of the load cell. The impact force time histories and strain time histories at the front section of each bottom rail for CT 5 at 1.95 m/s impact velocity are shown in Figure 2.14. Peak values for both load cell forces and the strains occur approximately at the same time. Also, forces can be calculated from the measured strains by multiplying by $EA_d$. Good agreement between these forces and the load cell responses was observed for CT 5 test
series; the measured forces based on average value of strain gauges on both East and West bottom rails (see Figure 2.3) were 87% of the peak load cell responses for CT 5 test series on average.

Figure 2.12. Measured peak impact force versus velocity for steel tube and shipping container elastic tests

Figure 2.13. Measured impact duration versus velocity for steel tube and shipping container elastic tests
2.4.2.2. *Inelastic response*

The peak impact force and duration from inelastic axial impact of the shipping container are shown in Figures 2.15 and 2.16, respectively. Two inelastic tests were carried out on the undamaged shipping container at a high impact velocity. The results revealed that the impact duration tends to increase during inelastic response of the container. The peak impact force measured from CT 6 and CT 9 at the velocity of 3.8 m/s was 1378 kN and 577 kN, respectively. The peak forces from CT 6 and CT 9 test series were 1.5 and 2.7 times higher than the total yield capacity of the axial member(s) subjected to the impact, respectively. The corrugated panels, corner posts and beams connected to the axial members of the container can make a significant contribution to the maximum capacity of the shipping container during inelastic axial impact. The maximum measured strain values were 0.0045 (strain gauge on bottom rail) and 0.0279 (strain gauge on top rail) for CT 6 and CT 9, respectively. The failure modes in the inelastic trials were due to the yielding and local buckling of the axial members, as shown
in Figure 2.17. Some impact tests were also carried out on the damaged container and the results are compared to the elastic test results. During the damaged container experiments at the lower impact velocities, there was no significant reduction in peak force values and also impact force varies linearly with velocity. Figure 2.17 shows the weld-line fracture and local buckling of the axial members from CT 8 and CT 10 test series.

**Figure 2.15.** Comparison of peak forces from elastic and inelastic shipping container impact tests

**Figure 2.16.** Comparison of impact duration from elastic and inelastic tests for shipping container
2.5. Discussion of results

2.5.1. Impact force and duration estimation

Comparison of the impact force model [Eq. (2.2)] and the elastic experimental results indicate that the model is accurate for elastic impact events. The accuracy of the impact force model is assessed by comparison of the measured and estimated equivalent stiffness for each debris type. The estimated stiffness ($k_d$) is computed from the measured material properties and geometry using Eq. (2.1) and is summarized in Table 2.4. Since the impact model does not take account of the contact stiffness, the wood pole experiments without contact materials (i.e., rubber or plywood sheets) were used herein. The average cross sectional area of the wood pole was used for the wood pole test series. The measured equivalent stiffness was calculated from Eq. (2.2) using the measured mass, impact
velocity, and peak impact force; the results are summarized in Table 2.4. The estimated equivalent stiffness was used to compute the estimated peak impact force using Eq. (2.2). The error of estimated peak impact force for each test series is listed in Table 2.4 by comparison with the experimental data. The error in estimated peak impact force is 5% or less for all test series. A similar comparison for the estimated (Eq. (2.3) and measured impact duration for the elastic trials is shown in Table 2.5. The error in impact duration varies 1% to 39% of estimated.

**Table 2.4. Error of peak impact force of the proposed model**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Estimated equivalent stiffness, $k_d$ (Eq. 2.1) (MN/m)</th>
<th>Measured equivalent stiffness (MN/m)</th>
<th>$R^2$ value</th>
<th>Error of estimated peak impact force</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT 1</td>
<td>129.9</td>
<td>128.8</td>
<td>0.999</td>
<td>0.4%</td>
</tr>
<tr>
<td>CT 2</td>
<td>85.6</td>
<td>79.6</td>
<td>0.982</td>
<td>3.7%</td>
</tr>
<tr>
<td>CT 3</td>
<td>41.3</td>
<td>44.8</td>
<td>0.989</td>
<td>-4.1%</td>
</tr>
<tr>
<td>CT 4</td>
<td>20.7</td>
<td>20.9</td>
<td>0.998</td>
<td>-0.6%</td>
</tr>
<tr>
<td>CT 5</td>
<td>88.7</td>
<td>94.0</td>
<td>0.994</td>
<td>-2.9%</td>
</tr>
<tr>
<td>Steel tube</td>
<td>25.2</td>
<td>26.8</td>
<td>0.999</td>
<td>-3.1%</td>
</tr>
<tr>
<td>Wood pole</td>
<td>59.0</td>
<td>65.3</td>
<td>0.984</td>
<td>-5.0%</td>
</tr>
</tbody>
</table>

Note: WT 1, 2, 4, and 7 were used for Wood pole experiments.

**Table 2.5. Error of impact duration of the proposed model**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Estimated duration (Eq. 3) (msec)</th>
<th>Measured duration (msec)</th>
<th>Coefficient of restitution (e)</th>
<th>Error of estimated impact duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT 1</td>
<td>8.4</td>
<td>9.1</td>
<td>0.56</td>
<td>-7.3%</td>
</tr>
<tr>
<td>CT 2</td>
<td>10.4</td>
<td>10.5</td>
<td>0.38</td>
<td>-1.0%</td>
</tr>
<tr>
<td>CT 3</td>
<td>14.9</td>
<td>12.9</td>
<td>0.21</td>
<td>15.6%</td>
</tr>
<tr>
<td>CT 4</td>
<td>21.1</td>
<td>17.0</td>
<td>0.08</td>
<td>24.5%</td>
</tr>
<tr>
<td>CT 5</td>
<td>10.2</td>
<td>11.0</td>
<td>0.48</td>
<td>-6.9%</td>
</tr>
<tr>
<td>Steel tube</td>
<td>2.6</td>
<td>2.7</td>
<td>0.82</td>
<td>-1.1%</td>
</tr>
<tr>
<td>Wood pole</td>
<td>3.7</td>
<td>6.1</td>
<td>0.82</td>
<td>-39.0%</td>
</tr>
</tbody>
</table>

Note: WT 1, 2, 4, and 7 were used for Wood pole experiments.
The measured peak impact forces and impact durations have been non-dimensionalized by the peak force and duration from the impact model [Eqs. (2.2) and (2.3), respectively]. Non-dimensionalized force-time histories for representative elastic trials are presented in Figure 2.18 for each impact case over a range of impact velocities. Time histories for each test series were comparable but clear differences exist between impact cases. The peak impact force occurred approximately at the middle of the impact duration for all test series. The approximate shape of the force time history for wood pole, steel tube and shipping container test series was half-sine, rectangular and trapezoid, respectively. The measured force-time history is compared to the impact model [Eqs. (2.2) and (2.3)] time history for debris-rigid structure impact for each case. The steel tube estimate is in good agreement with the experimental results. The peak impact force can also be predicted accurately by the proposed model for all test series. The ratio of experimental impulse to the impact model impulse (IR factor) is shown in Figure 2.18. Results indicate that the impulse from the proposed model is always conservative for all debris impact cases (i.e., IR < 1).

The non-dimensionalized peak impact force and duration (i.e., the ratio of measured value to estimated value) for wood pole test series are shown in Figure 2.19. The results show that the impact model provides a reasonable approximation for wood pole peak force. The estimated impact durations are lower than the measured values (i.e. non-dimensionalized value > 1) but the proposed method provides a reasonable estimate for the higher impact velocities.
Figure 2.18. Non-dimensionalized load cells histories for three types of debris: shipping container (CT), wood pole (WT), and steel tube (Note: $IR = \text{impulse ratio}$)
The non-dimensionalized values of peak impact force and duration at varying velocities for steel tube and shipping container elastic test series are shown in Figure 2.20. The results agree with the proposed 1D equivalent bar model. The measured impact durations for the container top corner(s) impact case are lower than estimated values. A substantial portion of the container total mass is distributed on the diaphragm including transverse beams and wooden floor, resulting in the lower \( e \) value for the container top corner(s) impact cases (see Table 2.5). Therefore, the estimated duration, which is based on \( e = 1 \), provides the higher values.

**Figure 2.19.** Non-dimensionalized measured values versus impact velocity for wood pole tests:

(a) peak impact force; and (b) impact duration
Figure 2.20. Non-dimensionalized measured values versus impact velocity for shipping container and steel tube tests: (a) peak impact force; and (b) impact duration

2.5.2. Response of the structural members

In order to design a structure for dynamic impact demands the equivalent static forces need to be determined. The equivalent static force and corresponding dynamic response factor are determined using the measured impact load histories and the estimated load histories. The results are compared to assess the conservatism of the model for different debris impact scenarios. The response of an undamped linear single-degree-of-freedom system (SDOF) with a natural period $T_n$ to average force time histories from the experiments was determined. The dynamic response factor $R_d$ (i.e., the ratio of maximum response of the SDOF system to the static displacement from the peak force) versus the ratio $t_d/T_n$ for debris axial impact forces of equal amplitude is presented in Figure 2.21. $t_d$ is the impact duration from Eq. (2.3). The $R_d$ factors for different impact cases were compared to the rectangular pulse force from the proposed model. The comparisons revealed that the dynamic response of the structural members due to the impact model time history is conservative for all axial impact cases. In order to specify the debris
impact design force an equivalent static force can be determined by multiplying $R_d$ (from rectangular pulse model) and $F$ [from Eq. (2.2)]. Moreover, the results are compared to the dynamic response factor from ASCE 7 (2010), as shown in Figure 2.21. The comparisons imply that the $R_d$ factor in ASCE 7 design provision is conservative for single corner container and wood pole impacts; however, it is unconservative for the unlikely cases of multi-corner container impacts.

![Figure 2.21. Response spectra for debris axial impact forces of equal amplitude](image)

2.6. Conclusions

A series of full-scale impact experiments were conducted on a wood utility pole, steel tube, and shipping container. The measured equivalent stiffness and impact duration of the debris are presented from experimental data. The results are used to validate a simple one-dimensional impact model that can be used in code provisions to estimate both the impact force and duration demands.
Based on the results of the present study, the following conclusions can be made:

1. Comparisons to the data indicate that the model provides an accurate estimate for peak impact force and a reasonable estimate of impact duration.

2. The wood test series indicates that the impact area does not influence peak impact force and duration during elastic impact.

3. Impact duration remains constant for steel tube and shipping container during elastic impact. But the wood tests reveal that the duration tends to decrease with increase in impact velocity due to rate sensitivity of wood.

4. The impulse is not significantly influenced by the contact stiffness. However, the peak impact force decreases and impact duration increases with reduced contact stiffness.

5. The inelastic impact results indicate that response of the debris at higher impact velocities results in higher impact durations and in a capped peak force.

6. Since the model assumes elastic impact, the estimate of impulse is always conservative (1.2 to 2 times higher than measured impulse from different debris impact cases).

7. The dynamic response factor due to the proposed rectangular pulse provides conservative design values for all debris impact cases.

8. The comparisons indicate that the dynamic response factor in ASCE 7 design provision is conservative for single corner container and wood pole impacts; however, it is unconservative for the unlikely cases of multi-corner container impacts.
CHAPTER 3

Estimation of Demands Resulting from Inelastic Axial Impact of Steel Debris

3.1. Introduction

Current U.S. design guidelines (ASCE 2010; FEMA 2011, 2012) use simple approaches to estimate water-borne debris impact forces, but there is no consensus on the specification of the design force (Piran Aghl et al. 2013). The peak impact force estimated by the impulse-momentum approach is $F = \pi m_d v/2\Delta t$ given in ASCE 7 (2010), where $m_d$ is the total mass of the debris, $v$ is the impact velocity, and $\Delta t$ is the time to reduce the debris velocity to zero; a value of 0.03 s is recommended for $\Delta t$ based on the log impact test results. Note that $\Delta t$ is half the impact duration ($t_d$, the time between the initial contact and the end of the contact) presented in this chapter. Based on Haehnel and Daly (2004), FEMA P646 (2012) specifies a peak impact force $F = v\sqrt{k m_d}$, using the contact stiffness approach in which $k$ is the effective contact stiffness of the debris and structure. For 20-ft shipping container, a value of 85 MN/m is provided for $k$ in FEMA P646 (2012). Debris impact force estimation methods provided by current design guidelines do not explicitly take into account the inelastic response of the debris. However, shipping containers and other debris are unlikely to remain elastic during impact, especially at elevated impact velocities. Therefore, it is important to characterize
the inelastic behavior of the debris during impact to be able to estimate properly the debris impact loads imposed on a structure in the inundation zones.

In previous chapter, full-scale in-air axial impact tests of a wood utility pole, steel tube and shipping container were conducted. The main focus was on the elastic behavior of wood poles and shipping containers, and a simplified elastic model for debris impact force estimation was developed (Piran Aghl et al. 2014a; Riggs et al. 2013; Paczkowski et al. 2012).

This chapter presents the results of impact demands from nonlinear dynamic FE simulation of simplified and complex debris-type models. A steel tube is used as a simplified debris type. The tube represents a uniaxial structural component that is not influenced by non-structural attachments and is representative of a component of the steel debris present in a tsunami debris flow. The tube dimensions are chosen to represent the axial properties of a component of a shipping container. A standard shipping container is employed as the baseline complex model in the present study. The container model consists of all structural and non-structural components along with associated connection details. In this study, in-air axial impact of debris is examined. The FE models are validated by comparing computed responses with the results from full-scale in-air debris impact experiments (Piran Aghl et al. 2014a). Different axial impact cases of the shipping container are considered to examine the inelastic response under impact velocities up to 15 m/s. The simulated impact forces are compared to the estimated values from current design guidelines. A one-dimensional bar model is developed, illustrated, and validated using the simplified debris consisting of a steel tube to estimate the debris
impact demands under inelastic response. The proposed model is then extended to apply to complex debris-types and validated using the experimental and simulation results of the shipping container impact.

3.2. Equivalent one-dimensional inelastic bar model

A simplified dynamic model is used to provide an accurate estimate of the debris impact demands. Previously, an equivalent 1D linear elastic bar model was developed and validated by experimental data. In this chapter, an equivalent 1D inelastic bar model is proposed to account for the inelastic response of the debris during axial impact. The debris is modeled as a uniform inelastic bar of length $L$, cross sectional area $A$, mass $m_d$, and equivalent stiffness $k_d$, subjected to axial impact. For complex debris such as a shipping container, an equivalent 1D inelastic bar model is defined that has a total mass of the debris $m_d$; $L$ is the length of the axial impacting member of the debris; and $A$ is the cross sectional area of the axial member(s) of the debris that are subjected to the impact. Figure 3.1 shows a schematic of the equivalent 1D inelastic bar impacting the structure. $k_s$ and $m_s$ are the structural stiffness and mass, respectively; $F$ is the impact force due to inelastic debris impact to the rigid structure; and $v$ is the impact velocity. Note that the proposed 1D model does not account for the localized contact stiffness of the target structural component at the location of the impact. Consequently, the 1D model provides a conservative estimation for debris impact forces.
Figure 3.1. Estimation of inelastic debris impact force using equivalent 1D bar model

The impact force for the elastic bar model is obtained from the solution of the one-dimensional wave equation (Riggs et al. 2013; Paczkowski et al. 2012). This formulation assumes that the projectile impacts a rigid structure (i.e., $k_s \to \infty$) and responds in a uniaxial mode. The impact force for the elastic bar model is $F_i = \rho c_i^2$, in which $\rho$ is the mass density of the equivalent bar; the elastic wave velocity (i.e., speed of
sound) in the bar \( c_e = \sqrt{E/\rho} \); \( E \) is the elastic Young’s modulus; elastic equivalent stiffness \( k_{de} = EA/L \); and mass \( m_d = \rho AL \).

During elastic axial impact, the compressive “elastic wave” propagates through the bar at the speed of \( c_e \). Stress waves generated at elevated impact velocities lead to a plastic response of the bar. As a result, a “plastic wave” propagates in the bar following an “elastic wave”. The speed of sound during plastic deformation of the proposed 1D inelastic bar model is

\[
c_p = \sqrt{\frac{\partial \sigma}{\partial \varepsilon}}
\]

in which \( \sigma \) is the stress and \( \varepsilon \) is strain. The estimation of debris peak impact force using an equivalent 1D inelastic bar model is presented in Figure 3.1. The peak force due to the impact of inelastic bar with a rigid structure is computed for different impact velocities. At the beginning of this computation, the force-deformation (\( F-u \)) or stress-strain (\( \sigma-\varepsilon \)) relationship of the inelastic bar is required. Figure 3.1 illustrates the idealized multi-linear force-deformation and stress-strain curves. \( k_{di} \) and \( E_i \) are the equivalent stiffness and modulus for each linear segment \( i \), respectively. Impact force increment \( \Delta F_i \) and impact velocity increment \( \Delta v_i \) corresponding to the segment \( i \) are computed as presented in Figure 3.1. The debris peak impact force applied to the structure is given by

\[
F_{i+1} = F_i + \Delta F_i
\]

in which \( F_{i+1} \) is the peak impact force corresponding to the segment \( i \).
For cases where the force-deformation relationship of the bar can be represented by two segments, a simplified 1D bilinear model can be used. Taking the secondary modulus as $E_p$, the stiffness of the equivalent bilinear bar after initial yield (i.e., secondary equivalent stiffness) is $k_{dp} = E_p A / L$. The impact velocity leading to an initial yielding of the bar is

$$v_y = \varepsilon_y c_e = \frac{F_y}{\sqrt{m_d k_{de}}} \tag{3.3}$$

in which $v_y$ is the yield velocity, $\varepsilon_y$ is the yield strain, and $F_y$ is the yield axial force of the equivalent bilinear bar. Using Figure 3.1 and Eq. (3.2), the simplified equation to estimate peak impact force for the bilinear bar is

$$F = \begin{cases} 
vc_e \rho A = v \sqrt{m_d k_{de}} & v \leq v_y \\
 v_y c_e \rho A + (v - v_y) c_p \rho A = v_y \sqrt{m_d k_{de}} + (v - v_y) \sqrt{m_d k_{dp}} & v > v_y 
\end{cases} \tag{3.4}$$

For linear impact against a rigid structure, the solution of the one-dimensional wave equation results in a constant value of impact force during the entire duration (i.e. rectangular pulse force). The duration is defined here as the time between the initial contact of the debris with the structure and the end of the contact (i.e., when impact force becomes zero). For simplicity, a rectangular pulse is assumed here and the duration is estimated by Eq. (3.5), which is based on impulse-momentum. Based on the measured response discussed in section 3.6.2, the coefficient of restitution, $e$, is taken to be equal to zero for inelastic response of the debris. Debris which remains elastic can be assumed to have a coefficient of restitution of 1.0.
\[ t_d = \frac{(1 + e) v m_d}{F} \] (3.5)

3.3. Experimental program

The experimental results of the full-scale impact tests on a 6.1 m steel tube and an ISO shipping container, presented in previous chapter, is used herein. The steel tube, which had approximately the same cross sectional area as the longitudinal members of the shipping container, was included as a debris-type to better understand the impact characteristics of the structural members of the shipping container. All experiments involved in-air axial impacts of the debris against load cells. Figure 3.2 shows the pendulum impact test setup. Steel plates were welded to the container’s corner fittings to have uniform contact between the container and load cells. Six series of axial impacts of the shipping container were carried out. These six cases included simultaneous impact to all four corners, three corners, two bottom corners, two top corners, one bottom corner, and one top corner of the container. The impact velocity for each case was increased up to the yield of the axial member of the container (i.e., corresponding yield velocity). Two impact trials at elevated impact velocities were performed to investigate the inelastic behavior of the shipping container during head-on impact. The steel tube tests consisted of only elastic axial impacts against a load cell.
3.4. Finite element modeling of debris impact

Three-dimensional nonlinear finite element models of the steel tube and the shipping container were developed using ABAQUS Explicit 6.13 to investigate the effect of inelastic debris behavior on the impact demands generated.
3.4.1. Load cell finite element model

In this study, all of the simulations involved axial impact of the debris against a robust load cell. The load cell assembly was modeled as a load cell body and a faceplate, as shown in Figure 3.3. Elastic material was utilized in modeling the load cell. The internal structure of the load cell body was not known, however the natural frequency and axial stiffness of the load cell were provided by the manufacturer. Consequently, the load cell body was modeled as a solid cylinder with a length equal to the overall load cell length. The density and elastic modulus of the load cell model was modified (4221 kg/m³ and 896 GPa, respectively) to match the global stiffness and frequency noted by the manufacturer (52,500 MN/m and 32 kHz, respectively). A faceplate was included on the load cell model that matched the geometry and material properties of the physical cell to ensure that contact properties were not affected. The density, elastic modulus and Poisson’s ratio of the load cell faceplate were 7850 kg/m³, 197 GPa, and 0.27, respectively, based on the load cell manufacturing specifications. The six-node solid wedge element (C3D6) is used for the load cell FE model. The rear of the load cell was fixed and the debris was assigned with an initial horizontal velocity. The impact force from FE analysis is determined from the contact force between the load cell model and the debris impact face.
Figure 3.3. Steel tube and load cell mesh details and steel tube responses at 0.2 ms after impact

(Normalized Stress = von-Mises stress / yield stress)

3.4.2. Steel tube finite element model

A FE model of the 6.1 m (20 ft) steel tube specimen was created using the eight-node solid brick element (C3D8R). The material properties of the steel tube were mass density 7850 kg/m$^3$, Young’s modulus 200 GPa, Poisson’s ratio 0.3, and yield strength 315 MPa (ASTM A500 2013). To assess the effect of nonlinearity on impact force, two material models were used in the analysis: an elastic-plastic hardening (EPH) model with tangent modulus 440 MPa and an elastic-perfectly plastic (EPP) model.

3.4.3. Shipping container finite element model

The 20-ft ISO standard shipping container was modeled considering all structural components present on the experimental test specimen. As shown in Figure 3.4a, the
shipping container model consisted of four vertical corner posts, eight corner fittings, four longitudinal members made up of two top side rails and two bottom side rails, corrugated steel sides, a top panel, a door end, and a plywood floor with steel cross members and a longitudinal beam. The measured section details of the major structural members of the container are shown in Figure 3.4b. The main members of the shipping container, including the top and bottom side rails, were made of Corten A steel (ASTM A242 2013). Tension coupon tests were performed to determine the material properties of the axial members of the container: the average value of yield strength and tensile strength were 381 MPa and 519 MPa, respectively; the elastic modulus was measured to be 207 GPa; and the fracture strain was 25%. Since the FE simulations were performed based on a large-deformation and large-strain formulation, the true stress and true strain data was used for all members of the container model. The mass density and Poisson’s ratio of the container materials were chosen to be 7800 kg/m³ and 0.3, respectively.

Four-node shell elements (S4R) were used for the majority of components of the shipping container model. The corner fittings of the container model were modified by attaching four steel plates using eight-node solid brick elements. The container model consisted of 36,687 nodes and 37,410 elements. The internal contact between various components of the container was established in the model using general-contact definition in ABAQUS. A contact definition was also defined between the load cells and corner fittings of the shipping container using a Coulomb friction value of 0.21, which is a frictional coefficient for steel sliding on steel (Yuan et al. 2008). The container model
included strain-rate effects on Corten A materials by considering 10% increase in the strength of steel at the strain rate of $1 \text{s}^{-1}$ (Brockenbrough and Johnston 1968).

**Figure 3.4.** (a) The shipping container model with structural details (wooden floor panel and west
3.5. **Comparison of numerical and experimental results**

Impact force-time histories and strain-time histories from in-air axial impact experiments are used to determine the accuracy of the steel tube and shipping container FE models.

During the steel tube tests, strain-time histories were measured using resistance-based strain gauges at three cross sections along the length of the steel tube: 30 cm from the front, in the middle, and 30 cm from the rear. Each cross section was instrumented with two strain gauges at the top and bottom of the tube (see Figure 3.5a). The average values were used to represent the corresponding strain-time history at each cross section.

Measured strain-time histories from the steel tube experiments at three cross sections (front, middle and rear) are compared to the strain-time histories from the FE model in Figure 3.5a. The strain histories from the FE simulations correspond to the elements at the location of the strain gauges. The force-time history from the steel tube experiment for an impact velocity of 2.2 m/s and the corresponding FE model results under elastic response are shown in Figure 3.5b. These comparisons of the force and strain magnitudes and durations served to validate the FE model. Additionally, the close comparisons confirmed that the model of the load cell was adequate for the present purposes.
Figure 3.5. Comparison of the numerical and experimental results during elastic impact of the steel tube at 2.2 m/s: (a) strain-time histories, and (b) impact force-time histories.

Comparisons of force-time histories between the elastic shipping container experiments and FE model are shown in Figure 3.6. All six series of axial impact are presented at the same impact velocity of 1.5 m/s. It is seen that the overall force-time history response from the experiments and FE simulations are similar. The peak impact force from the FE simulations is conservatively higher than the experiments (average increase of 9%). The impact duration of the numerical model agrees well with the
experiments (average error of 7%). Two trials (two bottom corner impact and one top corner impact) were conducted with an impact velocity of 3.8 m/s to validate the inelastic behavior of the FE model; see Figure 3.7. Comparison of the responses indicates that the FE model is also accurate at replicating the impact force response during inelastic response of the debris. Moreover, measured strain-time histories from shipping container experiments at impact velocities of 1.5 m/s and 3.8 m/s were compared to the strain-time histories from FE model, as shown in Figure 3.8. The strain gauges were longitudinally mounted on the bottom side and top side rails at the distance of 48 cm from the impact face. Figure 3.4b shows the cross sectional location of the strain gauges. The comparisons of the strain-time histories presented in Figure 3.8 indicate that the results of FE simulations correlate well with the experimental results during both elastic and inelastic response of the shipping container.
Figure 3.6. Comparison of the force-time histories from shipping container elastic experiments and FE simulations at 1.5 m/s

Figure 3.7. Comparison of the force-time histories from shipping container inelastic experiments and FE simulations at 3.8 m/s
Figure 3.8. Comparison of the numerical and experimental strain-time histories of the shipping container: (a) elastic impact at 1.5 m/s, and (b) inelastic impact at 3.8 m/s

3.6. Numerical simulation and discussion

3.6.1. Steel tube impact results

The steel tube results are used to investigate the response of a simplified debris type under impact and the accuracy of the numerical and simplified approaches for estimating the maximum force. Figure 3.3 illustrates the stress wave propagation through the steel tube under elastic and inelastic response at impact velocities of 6 m/s and 12 m/s,
respectively. Both stress distributions are shown at 0.2 ms after impact. As illustrated, the stress wave remains elastic under the lower impact velocity; however, as the impact velocity increases and the material exceeds yield the elastic stress wave is followed by an inelastic stress wave. This behavior is in line with the concept used for the simplified inelastic model. Figure 3.9 shows the peak impact force from both elastic-plastic hardening (EPH) and elastic-perfectly plastic (EPP) steel models with the yield capacity of 245 kN. The comparison between experimental and simulation results shows that the elastic response is accurately modeled by the numerical model. During elevated impact velocities the tube behaves in an inelastic manner. The response is characterized by yielding or strain hardening for the EPP and EPH models, respectively. This is followed closely by local buckling of the tube section as shown in the inset of Figure 3.9. The results of FE simulation indicate that the peak impact force under inelastic response is in line with the constitutive model and is not influenced by the occurrence of local buckling. Thus, the peak impact force is limited to the maximum strength of the material used.

**Figure 3.9.** Estimated and measured peak impact force for steel tube debris (local buckling of EPH model at 14 m/s shown)
3.6.2. Shipping container impact results

To evaluate the demands generated from the impact of a shipping container all six axial cases were considered and compared to the numerical and analytical approaches. The experimental tests were limited to an impact velocity of 3.8 m/s due to safety considerations during testing. The model simulations were extended to examine the behavior at velocities up to 15 m/s.

The numerical model provides an accurate representation of the forces and response observed in the experimental program. Damage distribution of the shipping container during axial impact from both experiment and FE simulation is shown in Figure 3.10. As illustrated, the experiment results in local damage to the bottom side rail of the container. This response is replicated in the numerical model as the container yields and crumples under large deformation. The accuracy of the force estimation and duration was demonstrated previously under both elastic and inelastic responses (see Figures 3.6 and 3.7). The container FE simulation indicated the maximum strain rate of 5 s$^{-1}$ at a side rail cross section for an impact velocity of 15 m/s.
The simulated shipping container impact force-time histories for all six impact cases at an impact velocity of 12 m/s are shown in Figure 3.11. These responses are all in the inelastic range of the container. The single corner impact cases result in lower impact forces and higher impact durations in comparison with multicorner container impacts. The relationship between impulse and impact velocity for inelastic impact is shown in Figure 3.12. The impulse is defined as the area under the force-time history over the defined impact duration. The impulse varies linearly with velocity with the average slope of $1.12 \, m_d$ for all inelastic impact cases ($\text{Impulse} = 1.12 \, m_d \, v$). In other words, the average coefficient of restitution ($e$) for container inelastic impact cases is 0.12. For two
and four corner impacts the impulse is bounded between an impulse computed with a coefficient of restitution of 0 and 1.0. For some single corner impact cases the simulated impulse is less than the lower bound impulse curve. This can be attributed to the fact that the center of the debris mass continues to have a forward velocity when the container separates from the load cell due to twisting of the container.

\[ \text{Impulse} = 2m_d v (\varepsilon = 1) \]

\[ \text{Impulse} = m_d v (\varepsilon = 0) \]

**Figure 3.11.** Impact force-time histories of shipping container at 12 m/s

**Figure 3.12.** Impulse versus impact velocity for shipping container during inelastic axial impact
3.6.2.1. Shipping container peak impact force

The measured and estimated relationship between peak impact force and impact velocity for each container impact case is presented in Figure 3.13. The results from FE simulations are compared with the experimental results and the estimated peak impact forces from ASCE 7-10 and FEMA P646. The peak forces from FE model results agree well with the experimental data. The peak force varies linearly with the velocity for single corner and multicorner container impact cases with impact velocity less than 1.5 and 2 m/s, respectively. For the higher impact velocities the inelastic response of the container leads to a significant reduction in peak impact force values. The estimated peak forces from design guidelines do not take into account the inelastic behavior of the container. As a result, the peak impact forces estimated for a shipping container using FEMA P646 are overly conservative for all container inelastic axial impact cases, especially for the likely cases of single corner impact. In addition, these comparisons show that the peak impact forces from ASCE 7-10 are unconservative for single corner impact cases with impact velocities less than 6 m/s and for all multicorner impact cases.

It should be noted that the head-on corner impact of the container represents the worst-case scenario for the container impact since only the main axial members of the container dominate the response. The impact demands presented in Figure 3.13 are larger than the simulated peak forces from impact of a 20’ shipping container with a concrete column in (Madurapperuma and Wijeyewickrema 2013). This is because the impact demands were dominated by flexural response of a transverse member of the container.
3.6.2.2. *Shipping container impact duration*

The impact duration due to container axial impact from FE simulations and experimental results are shown in Figure 3.14. The impact duration remains constant during elastic impact, whereas the impact duration tends to increase with impact velocity during inelastic impact. Also, the results show that the impact duration suggested by
ASCE 7-10 is much higher than the impact duration due to shipping container axial impact.

![Graphs showing impact duration for different axial impact cases of shipping container](image)

**Figure 3.14.** Impact duration for different axial impact cases of shipping container

### 3.7. Proposed impact demand estimation for inelastic axial debris impact

In this section, the proposed equivalent 1D inelastic bar model was used to estimate the impact demands during inelastic axial impact. The accuracy of the equivalent 1D
model is evaluated by comparison of the estimated values and validated FE simulation results. It is important to note that the FE analysis used the geometry and manufacturer reported stiffness and natural period for the load cell. Since the load cell stiffness and natural period were more than two orders of magnitude greater than the debris, in the 1D model the cell is considered to be rigid.

3.7.1. Peak impact force estimation

The peak impact force for both EPP and EPH steel tube models was estimated using Eq. (3.4). Figure 3.9 shows the comparison between the estimated values and FE results. The comparison indicates that the equivalent 1D bar model provides a close approximation of the numerical results during inelastic axial impacts.

To estimate shipping container peak impact force using the equivalent 1D inelastic bar model, the force-deformation relationship corresponding to the axial member(s) of the container that are subjected to the impact is required. This could be approximated from the structural and material properties of the main members; however, this approach neglects the contributions of the non-structural components. To determine a more accurate estimate of the force-deformation relationship for each impact case, a static numerical analysis of the container using ABAQUS was conducted. A static force was applied to the container impact region for each impact case. Nodes of the corner fitting(s) in the rear of the container were fixed to provide restraint against the applied static force. Figure 3.15 shows the force-deformation relationship for each axial impact case. The peak impact force versus velocity relationship for each axial impact case was determined
from the force-deformation relationships using the 1D inelastic bar model procedure outlined in Figure 3.1 and Eq. (3.2). Each force-deformation curve presented in Figure 3.15 is considered as a multi-linear curve to perform the computations. As shown in Figure 3.13, comparison of the 1D model and the numerical simulation results indicates that the equivalent 1D model provides a good approximation for the shipping container inelastic axial impact.

Figure 3.15. Static force versus axial deformation for different cases of shipping container axial loading

The 1D inelastic bar model results illustrated in Figure 3.13 are used to determine an elastic equivalent ($k_{de}$) and secondary equivalent stiffness ($k_{dp}$) for each container impact case. For each impact force-velocity curve associated with the 1D model illustrated in Figure 3.13, a bilinear curve was developed as follows. The impact force-velocity diagram was divided into two segments; an elastic segment followed by secondary segment beginning when the slope of the diagram exhibited a 5% deviation from the initial slope. A linear regression analysis was performed for each segment to determine
initial and secondary lines of the bilinear curve. Table 3.1 summarizes the values
determined from the bilinear curve and can be used along with Eq. (3.4) to estimate the
shipping container peak impact force for design applications.

**Table 3.1.** Parameters of the equivalent bilinear bar model for shipping container peak impact
force estimation

<table>
<thead>
<tr>
<th>Shipping container impact case</th>
<th>Yield impact velocity, $v_y$ (m/s)</th>
<th>Yield impact force, $F_y$ (kN)</th>
<th>Elastic equivalent stiffness, $k_{de}$ (MN/m)</th>
<th>Secondary equivalent stiffness, $k_{dp}$ (MN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Four corner</td>
<td>3.4</td>
<td>2301</td>
<td>197.3</td>
<td>5.0</td>
</tr>
<tr>
<td>Three corner</td>
<td>3.0</td>
<td>1584</td>
<td>123.8</td>
<td>2.9</td>
</tr>
<tr>
<td>Two bottom corner</td>
<td>2.9</td>
<td>1600</td>
<td>132.3</td>
<td>1.8</td>
</tr>
<tr>
<td>Two top corner</td>
<td>2.3</td>
<td>884</td>
<td>63.9</td>
<td>1.2</td>
</tr>
<tr>
<td>One bottom corner</td>
<td>2.4</td>
<td>868</td>
<td>59.3</td>
<td>0.4</td>
</tr>
<tr>
<td>One top corner</td>
<td>1.8</td>
<td>491</td>
<td>32.8</td>
<td>0.5</td>
</tr>
</tbody>
</table>

### 3.7.2. Impact force-time history estimation

The impact duration for shipping container impact is estimated using Eq. (3.5). Figure
3.14 shows the comparison between the estimated impact duration and simulation results.

To compare the shape of the impact force-time histories the impact forces and impact
durations from shipping container FE simulations have been nondimensionalized by the
estimated peak force and duration from the equivalent 1D bar model [Eqs. (3.2) and (3.5),
respectively]. Nondimensionalized force-time histories for container impact simulations
are presented in Figure 3.16 for impact velocities from 4 to 13 m/s. It can be seen that the
nondimensional rise time decreases as the impact velocity increases for each shipping
container impact case. The short rise time observed in the shipping container inelastic
response during high impact velocities is well represented by a sudden jump in the
proposed rectangular pulse. The peak impact force is also accurately estimated by the proposed model. Since a zero coefficient of restitution was assumed herein, the impact duration is underestimated for all cases; as illustrated previously in Figure 3.12, this assumption also leads to an underestimation of the impulse, especially for low impact velocities.

Figure 3.16. Nondimensionalized impact force-time histories for different inelastic axial impact cases of the shipping container
3.8. **Dynamic response of the structural members**

The force-time histories due to axial debris impacts exhibit that rise time and impact duration can be short in comparison with the natural period of common load-bearing structural members. Consequently, it is necessary to consider the dynamic effects when defining the design structural demands. The equivalent static force and corresponding dynamic response factor are determined using the simulated impact load histories and the estimated load histories. The results are compared to assess the conservatism of the proposed 1D model for different debris impact scenarios. Newmark’s linear acceleration method (Chopra 2007) was used to determine the response of an undamped linear single-degree-of-freedom system (SDOF) with a natural period $T_n$ to an average force-time history for each impact case. For a given impact case, the average force-time history was determined as follows. Force-time histories were computed for impacts between 4 to 10 m/s, and the time duration for each was normalized. These curves were then averaged to obtain the average force-time history for normalized time. The response of the SDOF system was then obtained for this average force history applied over the average simulated impact duration. This was done for each of the six impact cases. The dynamic response factor $R_d$ (i.e., the ratio of maximum response of the SDOF system to the static displacement from the peak force) versus the ratio $t_d/T_n$ for inelastic axial debris impact forces of equal amplitude is presented in Figure 3.17. The value of $t_d$ is the impact duration for inelastic debris from Eq. (3.5). The $R_d$ factors for simulated shipping container impact forces were compared to the $R_d$ for a rectangular pulse force corresponding to the proposed model. The comparison revealed that the dynamic
response of the structural members from the impact model time history is conservative for all inelastic axial impact cases. The results also indicated that although the impact duration \( (t_d) \) is underestimated as discussed in the previous section, the proposed rectangular pulse force from 1D model leads to a conservative \( R_d \) value for all shipping container impact cases. To specify the debris impact design force, an equivalent static force can be determined by multiplying \( R_d \) (from the rectangular pulse model) and \( F \) from Eq. (3.4). Moreover, the results are compared with the dynamic response factor from ASCE 7-10 flood chapter commentary (ASCE 2010), as shown in Figure 3.17. The comparisons imply that the \( R_d \) factor in ASCE 7-10 design provision (which is based on half-sine pulse force) is unconservative for container inelastic axial impact cases.

**Figure 3.17.** Response spectra for shipping container inelastic axial impact forces of equal amplitude
3.9. Conclusions

In this study, three-dimensional nonlinear dynamic FE models of the steel tube and shipping container were developed. The FE models are validated against the full-scale impact experiments previously reported in the literature. A series of inelastic axial debris impact analyses were conducted. The results show that as the impact velocity increases, the impact duration increases and the peak impact force is limited to the strength capacity of the axial member.

An equivalent 1D inelastic bar model is proposed to estimate the inelastic debris demands during axial impact. The FE simulations and previously reported experiments were used to validate the proposed model. It is found that the equivalent 1D inelastic bar model allows for an accurate prediction of the peak impact force. The 1D model underestimates the impact duration but is found to provide an adequate approximation for determination of the dynamic response of the structure.

The comparison between FE simulation results and estimated values from design guidelines indicate that the peak impact forces estimated for shipping container using FEMA P646 design provision are overly conservative for all container inelastic axial impact cases, especially for the most likely cases of single corner impact. It is also found that the peak impact forces from ASCE 7-10 design provision are unconservative for single corner impact cases with the impact velocity less than 6 m/s and for all multicorner impact cases. The proposed simplified 1D model is found to estimate peak impact force accurately for all scenarios and can be used to estimate impact demands from debris.
Analysis of a SDOF structural model subject to the debris impact demands indicates that the dynamic response factor computed using the 1D model provides a conservative equivalent static force for all container inelastic impact cases. Additionally, results indicate that the dynamic response factor provided by ASCE 7-10 flood chapter commentary is unconservative for container inelastic impact.
CHAPTER 4

A Simplified Model for Estimating Axial Impact Forces Resulting from Elastic Debris with Nonstructural Mass

4.1. Introduction

The estimation methods provided by current design guidelines do not explicitly account for the effect of magnitude and distribution of nonstructural mass (NSM) on impact demands. However, uniformly distributed mass along the entire length of the debris is unlikely especially for complex debris. Therefore, developing a model that accounts for the NSM is vital to predict accurately the debris impact demands.

The objective of this chapter is to investigate the effect of NSM distribution on axial debris impact under elastic and inelastic response. This chapter presents an experimental program in which in-air axial impact tests were conducted on a component of a shipping container with rigidly attached NSM. A steel tube is used to represent the main axial member of a shipping container and the attached NSM is representative of typical components connected to the member. The results are used to validate nonlinear dynamic finite element (FE) model that are extended for parametric evaluation. A simplified impact model is developed and validated by the experimental and simulation results to estimate the impact demands from debris with non-uniform NSM.
4.2.  Simplified one-dimensional impact model

A simplified dynamic model is utilized based on the one-dimensional (1D) stress wave theory to provide an accurate estimate of the axial impact demands of the debris with NSM. The debris is modeled as an elastic bar of length $L$, cross sectional area $A$, mass $m$, and elastic Young’s modulus $E$, subjected to axial impact at impact velocity $v$. Figure 4.1 shows a schematic of the 1D bar model impacting the rigid wall. The nonstructural mass $m_n$ is assumed to be uniformly distributed over the length of $0 \leq l_n \leq L$. The distance between the impact face and NSM is $d > 0$. The mass densities of the bar at the section without and with NSM ($\rho$ and $\rho_n$, respectively) are given by Eq.(4.1). The elastic wave velocity (i.e., speed of sound) in the bar at the section without and with NSM ($c$ and $c_n$, respectively) are given by Eq.(4.2).

\[ \rho = \frac{m}{AL}, \quad \rho_n = \frac{m}{AL} + \frac{m_n}{Al_n} \]  
\[ c = \sqrt{\frac{E}{\rho}}, \quad c_n = \sqrt{\frac{E}{\rho_n}} \]  

When the debris strikes the wall, an acoustic wave propagates from the impact face to the free end of the debris (see Figure 4.1). The impact force for the uniform elastic bar is obtained from the solution of the 1D wave equation (Paczkowski et al. 2012). For a bar with varying density, as presented in Figure 4.1, when the wavefront reaches the interface, part of the wave is reflected and part transmitted. The proportions of the
incident wave that are reflected by the interface and transmitted to the second material are expressed by reflection and transmission coefficients, $C_r$ and $C_t$, respectively (Achenbach 1973). The coefficients are given by Eq. (4.3) for the bar presented in Figure 4.1, in which $\Gamma$ is the ratio of the second material density to the first material density.

\[
\frac{\beta}{\beta} \quad \frac{-}{-} \quad \frac{-}{-} \quad (4.3)
\]

The initial impact force $F_0$ at the time $t = 0$ (when the initial stress wave starts propagating toward the free end of the bar) is

\[
(4.4)
\]

**Figure 4.1.** One-dimensional impact model of debris with nonstructural mass (NSM)

The stress wave ratio ($R$) is defined as a ratio of stress waves returning to the impact face to the initial stress wave $\sigma_0$. Figure 4.2 shows the schematic representation of the propagation of a single wavefront for five different cases and defines the stress wave ratios for each case. Cases 1 and 2 represent the wave path for the first returning wave in compression and tension, respectively. In case 3, the initial wavefront propagates along the entire length of the debris, reflect back at the free end and return to the impact face.
The stress wave ratios versus density ratio $\rho_n/\rho$ are presented in Figure 4.3. It is shown that the stress wave ratio in case 1 ($R_1$) results in a compressive stress. Therefore, for case 1 the magnitude of impact force increases when the returning wave reaches the impact face. This case represents the first compressive returning waves. The returning waves are fully reflected by the rigid wall (i.e., $C_r = 1$). Therefore the reflected wave in case 1 propagates back and forth. In case 1, the impact force due to the reflected waves after the $i$-th reflection from the wall is

$$ (i)F_r $$

$$ (4.5) $$

---

**Figure 4.2.** Definition of stress wave ratios for different wave paths along the debris length.
Figure 4.3. Comparison of stress wave ratios for different cases of returning waves

Figure 4.3 indicates that the returning waves in cases 2-5 are tensile stresses, contributing to a reduction in magnitude of the impact force. For case 3, large proportion of the initial stress waves returns to the impact face at the corresponding time $t_3$ for relatively low values of the density ratio $\rho_n/\rho$. This results in a debris separation from the wall since the impact force becomes tensile. Figure 4.3 also shows that the tensile stress due to the returning wave in case 2 is larger than returning stress waves in cases 4 and 5. The first reduction in magnitude of impact force is due to the returning wave in case 2 and can be determined as $2F_0R_2$, where $R_2$ is the stress wave ratio in case 2. In Figure 4.4, the total impact force-time history is divided into three force histories: initial impact force $F_0(t)$, impact force due to returning waves in case 1 $F_r(t)$, and impact force due to returning waves in other cases $F_i(t)$. The reflection time $t_r$ and transmission time $t_t$ are defined as the time taken to reach the impact face by the first reflected and transmitted waves, respectively [see Eq. (4.6)]. In other words, $t_r$ and $t_t$ correspond to the traveling time for the wavefront in cases 1 and 2, respectively.
The peak impact force \( F_p \) illustrated in Figure 4.4 can be determined as

\[
t_r = \frac{2d}{c}, \quad t_t = 2\left(\frac{d}{c} + \frac{l_n}{c_n}\right)
\]

(4.6)

in which \( N \) is the number of occurrences of a wave reflection from the wall within the time duration \( t_t \). When \( d \to 0 \) and therefore \( N \to \infty \), the asymptotic value of \( F_p \) is

\[
F_p = vcpA\left(1 + 2 \sum_{n=1}^{N} R_1^n \right)
\]

(4.7)

When the total impact force becomes tensile, the impact is over and the total duration can be computed. The total impact duration for a typical force history shown in Figure 4.4 is equal to \( t_3 \), however for relatively high values of density ratio \( \rho_n / \rho \) the impact duration is sensitive to the location of NSM (i.e., \( d \) in Figure 4.1). For the constant values of \( m_n \) and \( t_3 \), increasing the distance between NSM and impact face leads to an increase in impact duration (Piran Aghl et al. 2014b). Since the proposed 1D model is developed for design applications, a simplified approach is used to estimate the impact force history. It is assumed that the impact force decreases at a constant rate after reaching the peak impact force at time \( t_r \), as illustrated in Figure 4.4. To estimate impact duration, an impulse-momentum approach is used for the simplified 1D model. Since the elastic response is assumed herein, the total momentum of debris is \( 2(m+m_n)v \). By equating the
momentum with the area under the force-time history (i.e., impulse) of the simplified model presented in Figure 4.4, the debris impact duration $t_d$ of the simplified 1D model can be estimated by

$$
(4.9)
$$

**Figure 4.4.** Idealized impact force-time history of debris with nonstructural mass using 1D model

### 4.3. Experimental program

To investigate the effect of NSM on debris impact demands, experiments were conducted on a 6.1-m (20-ft) steel tube with different configurations of rigidly attached NSM under elastic response. A steel tube with approximately the same length and cross-
sectional area as the longitudinal members of a standard shipping container was utilized in the experimental program to better understand the impact characteristics of the structural members of the complex debris. The steel tube was a standard American Institute of Steel Construction rectangular hollow structural sections (HSS) 64 × 38 × 4.8 mm with the measured cross sectional area 7.68 cm$^2$. The mass of the steel tube was 39 kg and the modulus of elasticity was taken to be 200 GPa.

Figure 4.5 illustrates the experimental impact setup developed to represent the head-on debris impact. The impact was generated using a pendulum system. A predetermined impact velocity was generated by raising the debris to the desired height prior to release. To provide uniform contact between the steel tube and load cell, a 7.6 × 5.1 × 1.3 cm plate was welded to the impact face of the steel tube, as shown in Fig. 4.5.

To achieve sufficient resolution to accurately capture an impact event, data from all instrumentation (i.e., load cells, strain gauges, accelerometers, and light sensors) were recorded at 50 kHz. For each trial, impact velocity, force and duration from the load cell, and strain of the steel tube were measured.

A strain-based load cell was used to measure the impact force histories (see Figure 4.5). The global stiffness and frequency of the load cell provided by the manufacturer were 52,500 MN/m and 32 kHz, respectively. The first natural period of the load cell was well below the steel tube impact durations, resulting in an accurate representation of the impact forces by the load cell reading. The load cell was mounted on vertical members of the grillage and its location was adjusted to ensure axial impact of
the steel tube along the center of the load cell. Dynamic analysis of the grillage subjected
to the measured impact force histories at the location of the load cells revealed that the
displacement of the grillage during debris impact duration is negligible. Therefore, the
grillage can be assumed to act as a rigid structure in response to the steel tube impact.

Strain sensors were used to verify the measured impact force at the load cell and to
assess stress wave propagation in the steel tube. The steel tube was instrumented with six
resistance-based strain gauges at three cross sections along the length: 30 cm from the
front, in the middle, and 30 cm from the rear. Each cross section was instrumented with
two strain gauges at the top and bottom of the tube, as illustrated in Fig. 4.5. A light
sensor was used to determine the impact velocity at the time of first contact between steel
tube and load cell.

A total of 63 trials were conducted on the steel tube with and without rigidly attached
NSM. Steel plates were clamped along the length of the steel tube representing the rigidly
attached NSM, as shown in Fig. 4.5. Distribution of the NSM is achieved using lumped
mass attachments. The distribution is described relative to a uniformity distribution index
(UI) defined as

\[
UI = 1 - \frac{l_n/s}{L}
\]  

(4.10)
in which \( s \) is the number of cross sections along the length \( l_n \) with assigned lumped mass
attachments. \( L \) and \( l_n \) were previously illustrated in Figure 4.1. A value of \( UI = 1.0 \)
indicates that the NSM is uniformly distributed along length \( l_n \). \( UI = 0 \) represents a single
lumped mass as an NSM distribution along the entire length $L$. The effect of distribution of NSM on impact demands was assessed by conducting full and partial distribution of NSM along the length. Table 4.1 summarizes the test matrix for the steel tube experiments and provides the $UI$ values corresponding to each test series. An NSM percentage, listed in Table 4.1, is defined as a percentage increase of the debris mass due to the additional NSM.

![Figure 4.5. Experimental impact setup (units: cm)](https://example.com/figure4.5.png)

**Table 4.1.** Test matrix for elastic axial impact of steel tube with NSM

<table>
<thead>
<tr>
<th>Test Number</th>
<th>NSM distribution</th>
<th>Nonstructural mass (kg)</th>
<th>NSM percentage</th>
<th>$s$</th>
<th>$UI$</th>
<th>Impact velocity range (m/s)</th>
<th>No. of trials</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>N/A</td>
<td>0</td>
<td>0</td>
<td>N/A</td>
<td>N/A</td>
<td>0.16-2.76</td>
<td>17</td>
</tr>
<tr>
<td>T2</td>
<td>Uniform – full length</td>
<td>20.6</td>
<td>53</td>
<td>4</td>
<td>0.75</td>
<td>0.56-2.85</td>
<td>11</td>
</tr>
<tr>
<td>T3</td>
<td>Uniform – full length</td>
<td>41.2</td>
<td>105</td>
<td>8</td>
<td>0.88</td>
<td>0.59-2.15</td>
<td>10</td>
</tr>
<tr>
<td>T4</td>
<td>Uniform – full length</td>
<td>75.0</td>
<td>192</td>
<td>10</td>
<td>0.90</td>
<td>0.9-2.24</td>
<td>5</td>
</tr>
<tr>
<td>T5</td>
<td>Uniform – full length</td>
<td>135.0</td>
<td>345</td>
<td>18</td>
<td>0.94</td>
<td>0.77-1.93</td>
<td>6</td>
</tr>
<tr>
<td>T6</td>
<td>Uniform – front half</td>
<td>20.6</td>
<td>53</td>
<td>4</td>
<td>0.88</td>
<td>0.84-2.59</td>
<td>10</td>
</tr>
<tr>
<td>T7</td>
<td>Uniform – back half</td>
<td>20.6</td>
<td>53</td>
<td>4</td>
<td>0.88</td>
<td>0.47-2.77</td>
<td>4</td>
</tr>
</tbody>
</table>

Note: *Nonstructural mass includes the total mass of the plates and clamping hardware
4.4. Finite element modeling of steel tube impact

4.4.1. Numerical model

Three-dimensional nonlinear finite element model of the steel tube with NSM was developed using ABAQUS Explicit 6.13 (Dassault Systems) to investigate the effect of NSM distribution and nonlinearity on impact demands. The impact simulations involved axial impact of the steel tube against a load cell, as illustrated in Figure 4.6. The impact force from FE analysis is determined from the contact force between the load cell model and the steel tube impact face.

An FE model of the steel tube specimen was created using the eight-node solid brick element (C3D8R). The point mass was defined at the locations of the clamping hardware to model the rigidly attached NSM along the length of the steel tube. The uniformity distribution index of 0.95 was used for NSM distribution in the parametric study. The location of lumped mass is shown in Figure 4.6. The material properties of the steel tube were mass density 7850 kg/m3, Young’s modulus 200 GPa, and Poisson’s ratio 0.3. To assess the effect of nonlinearity on impact force, the measured plastic properties (true stress and true strain data) of the axial members of a standard shipping container (Piran Aghl et al. 2014c) were incorporated into the steel tube model; the yield strength and tensile strength were 381 MPa and 519 MPa, respectively; the fracture strain was 25%. A contact definition was defined between the load cell and steel tube impact face using a Coulomb friction value of 0.21, which is a frictional coefficient for steel sliding on steel (Yuan et al. 2008). The self-contact was also defined in the steel tube model since the
elements could be in contact under large deformations. Additionally, the steel tube model included strain-rate effects by considering 10% increase in the strength of steel at the strain rate of 1s\(^{-1}\) (Piran Aghl et al. 2014c). The inelastic behavior of the FE model of steel components was previously validated against the full-scale shipping container experiments in (Piran Aghl et al. 2014c).

![Figure 4.6. Steel tube and load cell mesh details and steel tube responses at 0.3 ms after impact](image)

4.4.2. **Validation of numerical models**

Impact force-time histories and strain-time histories from elastic axial impact experiments are used to determine the accuracy of the impact simulations of the steel tube with NSM. Comparisons of force-time histories between the experiments and simulations with an impact velocity of 2 m/s for different NSM distributions are shown in Figure 4.7. It is seen that the peak impact force, duration and overall force history response from the
experiments and simulations are similar. Additionally, measured strain-time histories from steel tube experiment T5 with 345% NSM at impact velocity of 2 m/s were compared to the strain-time histories from FE simulation, as shown in Figure 4.8. The comparisons indicate that the results of FE simulation of the steel tube with NSM correlate well with the experimental results.

**Figure 4.7.** Comparison of impact force-time histories from experiments and simulations for steel tube with impact velocity of 2 m/s

**Figure 4.8.** Comparison of experimental data and simulation results for steel tube with 345% NSM at 2 m/s
4.5. Experimental and numerical results

The peak impact force, impact duration, and impulse from the steel tube impact experiments and simulations are presented to investigate the effect of NSM magnitude and distribution on impact demands. The results of FE simulations with impact velocities up to 3 m/s are described in this section to evaluate elastic response.

Figure 4.6 illustrates the stress wave propagation through the steel tube with and without NSM distribution at impact velocity of 4 m/s. Both stress distributions are shown at 0.3 ms after impact. As illustrated, the NSM distribution on the steel tube contributes to the reduction in stress wave speed. In addition, the reflected waves due to the presence of NSM lead to an increase in stress near the impact region. This behavior is consistent with the concept used for the 1D model presented in Figure 4.1.

To assess the effect of NSM on speed of sound through the steel tube, the wave speed was computed from the measured strain histories at two cross sections along the specimen (rear and front); the difference in the stress wave arrival time between the strain gauges divided by the distance between two cross sections. Figure 4.9 compares the elastic wave speed from experiments with different NSM magnitude. It is evident that the increase in magnitude of rigidly attached NSM leads to a reduction in speed of sound.
Figure 4.9. Effect of NSM on wave speed along the steel tube

The relationship between peak impact force and impact velocity for steel tube with full and partial distribution of NSM are presented in Figures 4.10 and 4.11, respectively. The peak force varies linearly with the impact velocity for the steel tube with NSM. It also can be seen that the peak force increases as the magnitude of NSM increases but it is sensitive to the location of NSM. For the given magnitude of NSM, the peak force increases as the NSM is distributed closer to the impact face.

Figure 4.10. Peak impact force versus impact velocity for steel tube with full distribution of
The impact duration of the steel tube experiments and simulations are defined as the time between the initial contact of the steel tube with the load cell and the end of the contact (i.e., when impact force becomes zero). The impact duration of steel tube versus impact velocity for full and partial distribution of NSM are shown in Figures 4.12 and 4.13, respectively. For all cases of NSM distribution, the impact duration remains constant over the range of impact velocities. The impact duration increases as the NSM increases. Figure 4.13 shows the effect of the location of NSM on impact duration. Both the experimental results (T6 and T7) and the simulation results show that the duration increases as the distance between the NSM and the impact face (i.e., $d$ in Figure 4.1) increases.
The impulse ($I$) is defined as the area under the force-time history over the defined impact duration. The impulse values for steel tube with different NSM distribution are plotted against the initial momentum (i.e., $(m+m_n)v$), as shown in Figure 4.14. The results
are compared to the assumption used in the simplified 1D model (i.e., $I = 2(m + m_n)v$). The comparison indicates that the simplified 1D model provides a good approximation for the impulse.

![Figure 4.14. Relationship between impulse and momentum for steel tube with fully and partially distributed NSM](image)

4.6. **Impact force time history estimation**

In this section, the procedure outlined in Figure 4.4 for the simplified 1D model was used to estimate the impact demands. The lumped mass distribution along the full or partial length of the tube in experiments and simulations provide a non-uniform distribution of NSM. However, to estimate impact demands using the 1D model it is assumed that the NSM is distributed uniformly along the length $l_n$ (see Figure 4.1). The accuracy of the 1D model is evaluated by comparison of the estimated values with the measured and simulated results. The measured and simulated peak impact force and impact duration have been nondimensionalized by the peak impact force and duration from the 1D model [Eqs. (4.7) and (4.9), respectively]. Note that Eq. (4.8) is used to
estimate the peak force for impact cases with full and front-half distribution of NSM ($d = 0$).

The nondimensional peak impact force versus impact velocity is shown in Figure 4.15. The estimated values have been found to be in good agreement with the experimental and simulation results for steel tube with full and partial distribution of NSM.

Figure 4.16 presents the nondimensional impact duration at varying velocities for different magnitude and distribution of NSM. The results show that the 1D model provides a reasonable approximation for impact duration. For NSM partial distribution, the impact durations for front half and back half distribution are slightly overestimated and underestimated by the 1D model, respectively.

**Figure 4.15.** Nondimensionalized peak impact force versus impact velocity for steel tube tests and simulations
Figure 4.16. Nondimensionalized impact duration versus impact velocity for steel tube tests and simulations.

The estimated impact force-time history is compared to the measured and simulated force histories. Figure 4.17 shows the nondimensional force-time histories for different NSM magnitude and distribution over a range of velocities. As illustrated, the estimated impact force-time histories by the simplified 1D model are in good agreement with the experimental and simulation results.
4.7. Effect of nonlinearity on impact forces

Impact simulations of the steel tube with impact velocities up to 30 m/s were conducted to assess the effect of nonlinearity on impact force, impact duration and impulse. The steel tube consisted of 0%, 100%, and 300% NSM distributed along the entire length with the uniformity distribution index of 0.95 ($s = 20$).

The force-time histories for the impacts of the tube without NSM with initial velocities 10, 20, 25, and 30 m/s are shown in Figure 4.18. As illustrated previously, when the reflected elastic wave reaches the impact face during elastic response, the total stress in
the impact region becomes tensile and hence the tube separates from the wall. Therefore the impact duration does not vary with impact velocity under elastic response. However, as the impact velocity increases and the material exceeds yield the elastic stress wave is followed by plastic stress waves, which propagates at a lower speed. In this case once the reflected elastic wave reaches the impact face (at the time 2.5 ms) the total stress in impact region still remains in compression because of the presence of compressive plastic wave. This results in an increase in impact duration, as shown in Figure 4.18.

Under inelastic response, the elastic and plastic waves start to propagate simultaneously from the impact face. Hence the peak impact force occurs at the beginning of impact, as shown in Figure 4.18. This is followed by a reduction in impact force due to occurrence of “dynamic plastic buckling” (Jones 1989) of the tube section for relatively high impact velocities. The final buckled shape of the tube with impact velocity of 20 m/s is illustrated in Figure 4.18. It is also evident that the peak impact force increases as impact velocity increases due to material strain hardening and it is not influenced by the occurrence of dynamic plastic buckling during impact event.
Figure 4.18. Impact force-time histories for inelastic axial impact of the steel tube without NSM

Figure 4.19 compares the peak impact force for the steel tube with and without NSM during inelastic response. The peak impact force increases as the magnitude of the NSM increases. However, the sensitivity to the magnitude of NSM decreases as the peak impact force is governed by the plastic response of the tube at higher impact velocities. Therefore, the peak impact force is not influenced by the NSM for relatively high impact velocities and it increases only due to the strain hardening of the tube without NSM.

Figure 4.19. Peak force versus velocity for inelastic impact of steel tube with and without NSM
The impact durations due to impact of the steel tube with and without NSM are presented in Figure 4.20. For the steel tube with NSM, it can be seen that the impact duration remains constant for 100% and 300% NSM with impact velocities up to 12 m/s and 8 m/s, respectively. For this range of velocities, the impact ends when the first reflection of the initial elastic wavefront from the wall occurs. For higher impact velocities, the impact duration increases as a result of inelasticity.

![Impact duration versus impact velocity for inelastic impact of steel tube with and without NSM](image)

**Figure 4.20.** Impact duration versus impact velocity for inelastic impact of steel tube with and without NSM

The relationship between impulse and impact velocity is shown in Figure 4.21. It is evident that the impulse values are bounded between $(m + m_i)v$ and $2(m + m_n)v$. For high impact velocities a considerable portion of the impact energy is absorbed by the plastic deformation of the tube, contributing to a reduction in impulse. In this case the rebound velocity of the tube tends to be zero (i.e., coefficient of restitution is equal to zero).
In this chapter, a simplified one-dimensional model is developed to estimate the force time history generated from an axial impact of the elastic debris. The proposed model accounts for the location and magnitude of the nonstructural mass (NSM) attached along the length of the debris. The stress wave propagation in a 1D bar and impulse momentum approach are used to estimate peak impact force and impact duration, respectively.

A series of experiments on a 6.1-m steel tube with different configurations of rigidly attached NSM was carried out under elastic response. A three-dimensional nonlinear dynamic FE model of the steel tube with NSM was developed and validated with results from the experiments. The impact simulations consisted of elastic and inelastic impacts of the tube with NSM.

Figure 4.21. Impulse versus impact velocity for inelastic impact of steel tube with and without NSM
The experimental and simulation results were used to validate the 1D model. It is found that the 1D model provides a good agreement for peak impact force and impact duration and gives a conservative estimate of impulse. In addition, the estimated pulse shape correlates well with the measured and simulated results.

The results indicate that the peak impact force is influenced by the location of NSM and it can be well estimated by the 1D model. Also it is shown that the peak impact force is not affected by the NSM under inelastic response.

The simplified 1D model can be used to characterize the impact demands from debris with uniform and non-uniform nonstructural components.
CHAPTER 5

Effect of Nonstructural Mass on Debris Impact Demands: Experimental and Simulation Studies

5.1. Introduction

Massive objects such as large boats and vessels become adrift by the tsunami flow due to failure of mooring systems and therefore could become a serious hazard to coastal buildings (Naito et al. 2013). Shipping containers are widespread, especially in port locations, and therefore are considered a common debris-type in many coastal regions and can result in considerable dispersal and high likelihood of impact to structures. Standard 6.10 m (20 ft) shipping containers have a tare weight of 2300 kg and maximum gross weight of 30,500 kg. A fully loaded container has a nominal draft of approximately 1.58 m, and therefore it can easily float at moderate inundation depths and be a significant impact threat to structures. Severe damage to steel and reinforced concrete structural members due to shipping container impact has been observed (Robertson et al. 2007, 2012). The impact force induced by the floating debris is not well understood. Reliable estimation of the impact force demands from debris strikes is needed to improve the performance of the structural elements against such demands.

Previous studies on the evaluation of debris impact forces have mainly focused on empty debris-types. In spite of the fact that debris such as shipping containers, boats, and
barges can consist of a considerable amount of payload mass, the effect of nonstructural contents on the demands generated is not well understood. Vessel ‘debris’ impact has been examined through experimental and numerical studies of barge collisions with bridge piers. Full-scale experiments were carried out on a barge with varying payload mass to investigate the dynamic impact loads over a range of impact energies (Consolazio et al. 2006). Numerical simulation and dynamic analysis of the barge impact with varying mass were also performed. Influence of barge mass on impact demands was studied by considering a single degree-of-freedom (SDOF) point mass representing the total mass of the barge (Consolazio et al. 2005). The density of solid elements were changed during numerical simulations to study the effect of barge mass (Sha and Hao 2012, 2013). The study showed that the barge mass does not necessarily increase the peak impact force when the impact velocity is high. However, the effect of the attachment of the payload on the impact force was ignored in the analysis. Numerical investigations have been carried out to evaluate the forces during empty shipping container impact on a reinforced concrete column (Madurapperuma and Wijeyewickrema 2013). Formulae were obtained to estimate impact force and duration based solely on the simulation results. The effect of rigidly attached payload mass of the shipping container model under elastic response was numerically assessed and results have been compared with the estimated values from current design provisions (Piran Aghl et al. 2014b). The comparison indicated that the impact force estimation from current design guidelines is unconservative for the loaded shipping container during multicorner impact cases. A small-scale model of the shipping container was tested in a wave flume to investigate the effect of water on debris impact forces (Riggs et al. 2013; Ko 2013; Ko et al. 2014).
Unsecured steel plates were used as a payload to study the effect of content on impact force. It was found that the payload has no significant effect on measured peak impact force.

Methods for estimation of debris impact forces provided by current design guidelines do not take the effect of nonstructural contents into account. However, the nonstructural mass (NSM) can represent a substantial proportion of the total mass in debris such as shipping containers, and therefore play a key role in characterization of debris impact demands.

The primary focus of this chapter is the evaluation of NSM during elastic and inelastic axial impact of debris and development of a simple model that properly accounts for the contribution of the NSM on the impact load imposed on a structure. The present study presents an experimental program in which full-scale in-air axial impact tests were conducted on a loaded shipping container. The results are used to validate nonlinear dynamic FE models that are extended, when possible, for parametric evaluation. A simplified design-level model is developed to estimate the impact demands from debris with included NSM and is validated by the experimental and simulation results.

5.2. Simplified analytical impact model

A simplified dynamic model is used to provide an accurate estimate of the debris axial impact demands. In Chapters 2 and 3, an equivalent one-dimensional bar model was developed and validated by experimental and simulation results for elastic and inelastic debris impact. The debris is modeled as a uniform bar of length $L$, cross sectional area $A$, 

98
mass $m$, and equivalent stiffness $k_d$, subjected to axial impact. A schematic of the equivalent 1D bar is shown in Figure 5.1. $F$ is the impact force due to debris impact to the rigid structure and $v$ is the impact velocity. For a complex debris such as a shipping container, an equivalent 1D bar model is defined that has a total mass of the debris $m$; $L$ is the length of the axial impacting member of the debris; and $A$ is the cross sectional area of the axial member(s) of the debris that are subjected to the impact.

During elastic axial impact, the compressive elastic wave propagates through the bar at the speed of $c_e = \sqrt{E/\rho}$ (in which $E$ is the elastic Young’s modulus and $\rho$ is the mass density of the bar). Stress waves generated at elevated impact velocities lead to a plastic response of the bar. As a result, a plastic wave propagates in the bar following an elastic wave. The speed of sound during plastic deformation of the 1D bar is $c_p = \sqrt{(\partial \sigma / \partial \epsilon)/\rho}$, where $\sigma$ is the stress and $\epsilon$ is the strain. The impact force for the elastic bar model is obtained from the solution of the 1D wave equation and results in a constant value of impact force during the entire duration (i.e. rectangular pulse force). This formulation assumes that the projectile impacts a rigid structure and responds in a uniaxial mode. The impact force for the elastic bar model is $F = vc_e \rho A = v\sqrt{mk_d}$, where $k_d = EA/L$.

Estimation of peak impact force for inelastic bar model is demonstrated in Figure 5.1. The peak force due to the impact of inelastic bar with a rigid structure is computed for increasing impact velocities. For this computation, the force-deformation ($F-u$) relationship of the inelastic bar is required. Figure 5.1 illustrates the axial force-deformation curve for a sample debris simplified into multi-linear segments. $k_{di}$ and $E_i$ are the equivalent stiffness and corresponding modulus for each linear segment $i$. 

99
respectively. The impact force increment $\Delta F_i$ and impact velocity increment $\Delta v_i$ between each segment $i$ are computed as presented in Figure 5.1. The debris peak impact force corresponding at the start of the next segment $i+1$ is

\[ \Delta v_i = \frac{\Delta F_i}{\sqrt{mk_{di}}} \]

*Figure 5.1. Estimation of debris impact force using equivalent 1D bar model*

In this chapter, the equivalent 1D bar is used with a SDOF spring-mass system to account for the NSM and its connectivity to the debris. A schematic of the proposed equivalent NSM-spring bar model is shown in Figure 5.2. $k_s$ and $m_s$ are the stiffness and mass of the structural component subject to impact, respectively; $m_d$ is the empty mass of the debris; $m_n$ is the debris NSM; $c_n$ and $k_n$ are the damping coefficient and stiffness of the NSM-debris connection system, respectively. Figure 5.2 depicts three possible levels of connectivity between the NSM spring and the bar model. Case 1 consists of a NSM
which is free to slide on a surface with a coefficient of kinetic friction \( \mu \). An elastic-perfectly plastic spring with a yield force equal to the sliding friction force is assumed herein. Case 2 consists of a spring with \( c_n \) and \( k_n \) defined along the impact direction representing a NSM-debris restraint system. Case 3 assumes \( k_n \to \infty \), indicating no relative motion between the NSM and debris (i.e., rigidly attached NSM).

The force-time histories due to impact of debris are idealized using equivalent NSM-spring bar model, as shown in Figure 5.2. Primary and secondary rectangular pulse forces are considered for cases 1 and 2, and a single rectangular pulse force is assumed for case 3. \( I_p \) and \( I_s \) are the primary and secondary impulses, respectively. In this study the coefficient of restitution of the debris, \( e \), is assumed to be 1.0 for all cases. It should be noted that this assumption is conservative for inelastic impact.

For cases 1 and 2, at the end of the impact event, when the debris separates from the structure, the NSM may have a remaining velocity. The ratio of NSM velocity at the end of impact to the initial impact velocity, \( r_{vn} \), is defined by

\[
    r_{vn} = \begin{cases} 
    0 & \text{(case 1)} \\
    2IR - 1 & \text{(case 2)} 
    \end{cases}
\]

where \( IR \) is defined as the ratio of impulse of the NSM attachment spring force to the impulse of the corresponding “undamped linear” spring force. A damped linear spring with damping ratio \( \zeta \) is assumed for case 2 and therefore the impulse ratio can be estimated by \( IR = exp(-\zeta \pi/2) \) for small values of \( \zeta \) (Chopra 2007); it is obtained by the ratio of the damped spring peak force to the undamped peak force under initial velocity \( v \).
and zero initial displacement. For case 1, \( r_{vn} \) is equal to zero since it is assumed that the sliding NSM stops at the end of impact.

### 5.2.1. Primary pulse force estimation

Using Figure 5.1 and Eq. (5.2), the primary peak impact force \( F_p \) for cases 1 and 2, and the peak impact force \( F \) for case 3 are given as a function of impact velocity. Because of the fact that the rise time is very short during axial impact events, the influence of non-rigidly attached NSM (i.e. cases 1 and 2) on primary peak impact force has been neglected.

\[
F_{i+1} = \begin{cases} 
F_i + \Delta v_i \sqrt{m_d k_{di}} & \text{(cases 1 and 2)} \\
F_i + \Delta v_i \sqrt{(m_d + m_n) k_{di}} & \text{(case 3)}
\end{cases}
\]  

(5.2)

The primary impact duration \( t_p \) for cases 1 and 2 and impact duration \( t_d \) for case 3 are given by Eqs. (4.6) and (5.4), respectively. Impact durations are estimated based on an impulse-momentum approach and rectangular pulse shape.

\[
t_p = \frac{v m_d (1 + e)}{F_p}
\]  

(5.3)

\[
t_d = \frac{v (m_d + m_n) (1 + e)}{F}
\]  

(5.4)

### 5.2.2. Secondary pulse force estimation

Secondary impact duration \( t_s \) for cases 1 and 2 is estimated by Eq. (5.5). \( t_s \) for case 1 is defined as the time it takes for the sliding NSM with an initial velocity \( v \) to stop, which
is also equal to the time required to dissipate the initial kinetic energy of the NSM by friction. It is assumed that the ratio of debris acceleration to gravitational acceleration (g) is larger than coefficient of static friction so that the NSM sliding occurs. The total impact duration \( t_p + t_s \) for case 2 is equal to half the natural period of the linear spring system.

\[
t_s = \begin{cases} 
\frac{v}{\mu g} & \text{case 1} \\
\pi \sqrt{m_n/k_n} - t_p \geq 0 & \text{case 2}
\end{cases}
\]  

(5.5)

Secondary impact force \( (F_s) \) for cases 1 and 2 is estimated by Eq.(5.6). The NSM in case 1 is assumed to continue sliding till the end of impact duration and therefore the secondary force equal to the corresponding frictional force is considered. The secondary pulse shape for case 2 is simplified to the rectangular pulse and \( F_s \) is estimated based on an impulse-momentum approach.

\[
F_s = \begin{cases} 
\frac{\mu m_n g}{v m_n (1 + r_v) / t_s} & \text{case 1} \\
\frac{\mu m_n}{v m_n (1 + r_v) / t_s} & \text{case 2}
\end{cases}
\]  

(5.6)
5.3. Shipping container impact test

5.3.1. Experimental program

Full-scale experiments were conducted on a shipping container with two different types of payload to investigate the effect of NSM on the impact force, impulse, and duration. The container had a specified total mass of 2300 kg and a maximum allowable
gross mass of 30480 kg. All test series involved in-air corner impact of the shipping container against load cell(s). The impact was generated using a pendulum system and steel cables were used to suspend the container, as illustrated in Figure 5.3. In order to have a smooth contact between container and load cells, steel plates were welded to the corner fittings of the container. The load cells were mounted on steel wide flange cross-beams and attached to the reaction grillage.

In order to provide sufficient resolution to capture accurately an impact event, data from all instrumentation were recorded at 50 kHz. The impact force history was measured using high-frequency strain-based load cells. The impact velocity was determined at the time of initial contact between the container and load cell(s) using the average time-varying displacement of the container measured by two optical displacement sensors.

Figure 5.3. Full-scale empty and loaded shipping container test setup
Four series of axial impacts of the empty and loaded shipping container were carried out. The empty container test series consisted of impacts to the single bottom corner and two bottom corners of the shipping container. Inelastic response of the empty container during head-on impact was also assessed through trials at elevated impact velocities. Two different payload types were used and placed at the center of the wooden floor of the container during the loaded test series. As shown in Figure 5.4a, a water bladder was used without attachment to the container to represent the NSM case 1. Payload in the form of two 15 × 81 × 366 cm concrete panels were used with a wooden bracing system to represent the NSM case 2, as shown in Figure 5.4b. The wooden bracing system was installed between the concrete panels and the container front beam to prevent payload sliding. Table 5.1 summarizes the test matrix for the empty and loaded shipping container series.

![Figure 5.4. Shipping container payload: (a) water bladder (NSM case 1); (b) concrete panels with bracing system (NSM case 2)]
Table 5.1. Test matrix for empty and loaded shipping container series

<table>
<thead>
<tr>
<th>Test number</th>
<th>Load cell(s) position</th>
<th>NSM case</th>
<th>Payload mass (kg)</th>
<th>Container response</th>
<th>Impact velocity range (m/s)</th>
<th>No. of trials</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>One bottom corner</td>
<td>N/A</td>
<td>0</td>
<td>Elastic</td>
<td>0.75-2.1</td>
<td>9</td>
</tr>
<tr>
<td>T2</td>
<td>Two bottom corner</td>
<td>N/A</td>
<td>0</td>
<td>Elastic-inelastic</td>
<td>0.42-3.82</td>
<td>18</td>
</tr>
<tr>
<td>T3C1</td>
<td>Two bottom corner</td>
<td>case 1</td>
<td>2415</td>
<td>Elastic</td>
<td>0.26-1.52</td>
<td>11</td>
</tr>
<tr>
<td>T4C2</td>
<td>Two bottom corner</td>
<td>case 2</td>
<td>2177</td>
<td>Elastic</td>
<td>0.25-1.99</td>
<td>14</td>
</tr>
</tbody>
</table>

5.3.2. Experimental results

For each trial, impact velocity and force history of the container impact were measured. Impact force is determined from the measured response of the load cell(s). The impact force was accurately represented by the load cell reading since the first natural period of the load cell was well below the impact durations. Figure 5.5 illustrates the primary and secondary pulse forces due to the impact of a loaded shipping container. A typical impact force consists of a primary impulse $I_p$, secondary impulse $I_s$, total impulse $I_t$, primary duration $t_p$, and total impact duration $t_d$. The comparison of force-time histories from empty and loaded container test series with an impact velocity of 1.0 m/s is shown in Figure 5.6. Only a single (primary) pulse force was observed from the empty container test series, while the NSM used in the loaded container test series contributes to a secondary pulse force as well. Results also indicate that the presence of non-rigidly attached NSM has no significant influence on the primary pulse force. Since the duration of the primary pulse force for an axial container impact is very short, the non-rigidly attached NSM does not have enough time to affect the primary pulse. Peak impact force and impact duration of the primary pulse at varying velocities are shown in Figure 5.7 and Figure 5.8, respectively. The peak impact force varies linearly with velocity for the
empty and loaded container elastic test series. The results also indicate that the peak impact force is not changed by adding the payload. Figure 5.8 shows that the primary impact duration remains constant for both empty and loaded container tests. The impact duration is not affected by NSM for case 1, while an average increase of 17% is observed for case 2.

**Figure 5.5.** Definition of the primary and secondary impulses and durations for a typical impact force history

**Figure 5.6.** Measured impact force-time histories for empty and loaded container tests at 1.0 m/s

$$I_t = I_p + I_s$$
Figure 5.7. Measured primary peak impact force versus impact velocity for loaded and empty shipping container test series

Figure 5.8. Measured primary impact duration versus impact velocity for loaded and empty shipping container test series

Figure 5.9 shows the relationship between impulse and impact velocity for empty and loaded container tests. The total and primary impulses for each test series are compared. The primary impulse for each loaded container test series is 64% of the total impulse. Comparison between primary impulses of empty and loaded container tests shows that
NSM case 1 has no influence on the primary impulse, whereas NSM case 2 leads to an increase of 15%. The impulse values from experiments are also compared with the estimated impulse from the simplified 1D model for each impact case. The comparison indicates that the 1D model provides conservative impulse values for all cases.

![Figure 5.9](image-url)

**Figure 5.9.** Measured impulse for empty and loaded shipping container test series (solid symbols: $I_t = \text{total impulse}$, hollow symbols: $I_p = \text{primary impulse}$)

### 5.4. Finite element modeling of container impact

Three-dimensional nonlinear finite element model of the shipping container with contents was developed using ABAQUS Explicit 6.13 to investigate the effect of container contents on the impact demands generated. The numerical models were also validated against the full-scale experimental data. In this study, all of the simulations involved axial impact of the container against a robust load cell.

#### 5.4.1. Loaded container model
The 20-ft standard shipping container FE model, presented in Chapter 3, was used. Point mass and spring elements modeled the mass and connection type of the container contents. The total mass of the container contents was represented as 36 point masses uniformly distributed over the wooden floor, as shown in Figure 5.10. All three cases presented in Figure 5.2 are considered for NSM during loaded container impact simulations. For case 1 (sliding NSM), an elastic-perfectly plastic (EPP) spring with a yield force equal to the sliding friction force was assumed. A coefficient of kinetic friction of 0.5 was used between the wooden floor and water bladder. For the EPP spring, large values were chosen for $k_n$, so that an instantaneous yield force can be applied. For case 2 (tied NSM), a damped linear spring was used representing the connection system between concrete panels and the container. A damping ratio of 20% for the wooden bracing system was assumed (Stevenson 1980). The overall stiffness of the wooden bracing system and bottom front beam along the impact direction was calculated to be 6.3 MN/m. Therefore, the stiffness ($k_n$) and damping coefficient ($c_n$) for each spring element were 0.175 MN/m and 1.3 kNs/m, respectively. For case 3, the point mass was rigidly attached to the wooden floor.
Figure 5.10. Finite element model of shipping container: (a) structural framework; (b) configuration of lumped mass for loaded container (side panel is removed).
5.4.2. Validation of numerical models

Impact force-time histories from the in-air axial impact experiments were used to determine the accuracy of the shipping container FE models. Empty container simulations during both elastic and inelastic axial impact were validated in Chapter 3 using data from full-scale container impact experiments. Validation of loaded container impact simulations are presented herein. The experimental and simulated impact force-time histories for the shipping container with the water bladder with an impact velocity of 1.4 m/s are shown in Figure 5.11. The figure indicates that the numerical model for NSM case 1 is accurate at replicating both primary and secondary pulse forces during axial impact of the container. Figure 5.12 shows the experimental and simulated impact force-time histories for the container with concrete panels and an impact velocity of 2.0 m/s. The primary and secondary peak impact forces and durations are captured well with the simulation. The comparison reveals that the numerical model for NSM case 2 provides accurate results.

![Figure 5.11. Comparisons of impact force-time histories from loaded shipping container experiment T3C1 and FE simulation at 1.4 m/s](image-url)
Figure 5.12. Comparisons of impact force-time histories from loaded shipping container experiment T4C2 and FE simulation at 2.0 m/s

5.5. Numerical results and proposed impact demand estimation approach

5.5.1. Parametric study

A series of simulations are carried out to investigate the influences of payload mass, NSM connection type, impact velocity, and axial impact configuration (i.e., single corner or multcorner container impact) on the demands generated from the impact of a shipping container with contents. All three NSM cases were considered for one bottom and two bottom corner impact of a container. The loaded container impact experiments were limited to an impact velocity of 2 m/s and a payload mass of 2415 kg due to safety considerations during testing. For NSM case 1 (i.e., sliding mass), the model simulations were extended to examine the behavior of a half-loaded and fully loaded container at velocities up to 5 m/s. The total mass of the contents for the half-loaded and fully loaded container were 14,091 kg and 28,182 kg, respectively. For NSM case 2 (i.e. tied mass),
the validated numerical model was used to assess the inelastic behavior of the loaded container impact at velocities up to 8 m/s. The container model consisted of the same payload mass as experiment T4C2. Since the values of $k_n$ and $c_n$ employed in simulations were validated against the experiment T4C2 with specific payload mass, the NSM was not varied through parametric study. For NSM case 3 (i.e., rigidly attached), simulations of the empty, half-loaded and fully loaded container with impact velocities up to 6 m/s were conducted.

5.5.2. Simplified model for debris impact demand estimation

The proposed equivalent NSM-spring bar model was used to estimate the impact demands during axial loaded container impact. The accuracy of the simplified 1D model is evaluated by comparison with the experimental results when available and with the extrapolated FE simulation studies. It is important to note that the FE analysis used the geometry and manufacturer reported stiffness and natural period for the load cell. Since the load cell stiffness and natural period were more than two orders of magnitude greater than the debris, in the 1D model the load cell is considered effectively rigid.

To estimate shipping container peak impact force using the 1D model presented in Figure 5.1, the force-deformation relationship corresponding to the axial member(s) of the container that are subjected to the impact is required. The force-deformation curves for one bottom and two bottom corner impact cases were previously determined in Chapter 3 by conducting static numerical analysis of the container using ABAQUS. Using the force-deformation curves and the 1D model procedure outlined in Figure 5.1,
the primary peak impact force for each NSM case was determined as a function of impact velocity from Eq. (5.2). For NSM cases 1 and 2, Eq. (5.6) is used to determine the secondary peak force. Impact durations are estimated using Eqs.(5.3) to (5.5). As previously discussed in section 4.3, for NSM case 1, $\mu$ was equal to 0.5 and for NSM case 2, $k_n$ and $\zeta$ were 6.3 MN/m and 20%, respectively. Using Eq.(5.1), $r_{in}$ for NSM cases 1 and 2 were calculated to be 0 and 0.46, respectively.

5.5.3. Comparison of simulated and estimated results

The results of the loaded container impact simulations are presented in this section. To evaluate the accuracy of the proposed simplified 1D model, simulation results are compared with the analytical approaches for all three NSM cases.

5.5.3.1. Case 1: sliding NSM

The relationship between primary peak impact forces from FE simulations ($F_p$ shown in Figure 5.5) and impact velocity for the half-loaded and fully loaded container with NSM case 1 is shown in Figure 5.13. The peak force varies linearly with impact velocity for single corner and multicorner container impact cases with velocity less than 1.5 m/s. For the higher impact velocities the inelastic response of the container leads to a significant reduction in peak impact force values. The results indicate that the peak impact force is not affected by the NSM for case 1 attachment under both elastic and inelastic response. Figure 5.13 also shows the comparison between the simulated results and the estimated values provided by the simplified 1D model. The comparison indicates
that the 1D model provides an accurate approximation for single corner and multicorner impact of the loaded container for NSM case 1.

\[ \text{Figure 5.13. Primary peak impact force generated from one bottom and two bottom corner impact of the half loaded and fully loaded shipping container with NSM case 1} \]

The primary impact duration and total impact duration from simulations \((t_p, t_d)\) shown in Figure 5.5, respectively) are shown in Figure 5.14. Results indicates that the primary impact duration remains constant during elastic low velocity impact levels and increases with inelastic response at higher impact velocities (see Figure 5.14a); the total impact duration varies linearly with the impact velocity during both elastic and inelastic response when the container is loaded with sliding NSM (see Figure 5.14b). The simulation results also reveals that the primary and total impact durations are independent of the payload mass for NSM case 1. Figure 5.14 also compares the simulation results with the estimated impact duration from the 1D model. The comparison shows that the estimated values for primary and total durations correlate well with the simulated results.
Figure 5.14. Impact duration for the half loaded and fully loaded shipping container with NSM case 1: (a) primary impact duration; (b) total impact duration

The primary impulse and total impulse ($I_p$ and $I_t$ shown in Figure 5.5, respectively) versus impact velocity for half loaded and fully loaded container impact simulations are shown in Figure 5.15. The results show that the impulse varies linearly with impact velocity. For one bottom corner impact case, the primary and total impulses of the fully loaded container increased by 15% and 84% of the corresponding impulses for the half
loaded container, respectively. For impact of two bottom corners, changing the container payload mass from half-loaded to fully loaded resulted in an increase of 8% and 87% in primary and total impulses, respectively. The results illustrate that for the loaded container with NSM case 1 the total impulse is significantly affected by the payload mass. Figure 5.15 also shows the comparison between simulated results and estimated impulse values from 1D model. Figure 5.15a shows that the primary impulse from simulations is bounded between $mv_d$ (i.e., $e = 0$) and $2mv_d$ (i.e., $e = 1$). For low impact velocities the assumption of $e = 1$ provides a good approximation for the primary impulse but for higher velocities this assumption can be highly conservative. Figure 5.15b illustrates that the total impulse is estimated well with the 1D model for both half loaded and fully loaded container. In other words, the assumption of $r_{vn} = 0$ for sliding NSM provides a good approximation for total impulse and secondary impulse.

![Diagram](image-url)
5.5.3.2. Case 2: tied NSM

The relationship between primary peak impact force and impact velocity for one bottom and two bottom corner impact of the loaded container with NSM case 2 is presented in Figure 5.16. The results from FE simulations are compared with the experimental results and the estimated peak impact forces from the 1D model. The peak forces from the FE simulation results agree well with the experimental data under elastic response. The results for relatively low impact velocities show a linear relationship between peak impact force and impact velocity. However, for high impact velocities the peak impact force tends to reach a constant value. The estimated primary peak impact forces for NSM case 2 were calculated based on the mass of an empty container (i.e., $m_n = 0$) and correlate well with the simulated results. This indicates that for NSM case 2 the primary peak impact force was not influenced by the payload mass.
Figure 5.16. Primary peak impact force generated from one bottom and two bottom corner impact of the loaded shipping container with NSM case 2

The primary and total impact duration from experiments, simulations and 1D model are shown in Figures 5.17. Figure 5.17 shows a good agreement between simulations and experimental data for primary impact duration. It is observed that the primary impact duration tends to increase during relatively high impact velocities. The estimated primary impact duration from the 1D model provides an adequate approximation for one bottom and two bottom corner impact cases. Also, Figure 5.17 indicated a good match between simulation results and experimental data for total impact duration during low impact velocities. For relatively high impact velocities the total impact duration remains constant and it can be well estimated by the 1D model.
Figure 5.17. Primary and total impact duration for loaded shipping container with NSM case 2

The primary impulse and total impulse from simulations and experiments are compared in Figure 5.18. The simulation results have been found to be in good agreement with the results of experiments. Both primary and total impulses vary linearly with the impact velocity. The estimated values from the 1D model are also presented in Figure 5.18. Since the coefficient of restitution ($e$) is assumed to be 1.0, the 1D model provides a conservative estimate of the impulse, especially for high impact velocities.
Figure 5.18. Impulse for loaded shipping container with NSM case 2 (solid symbols: $I_t =$ total impulse; hollow symbols: $I_p =$ primary impulse)

5.5.3.3. Case 3: rigidly attached NSM

Figure 5.19 shows the relationship between peak impact force and impact velocity for one bottom and two bottom corner container impacts. The results of empty container simulations are compared with the data from test T1. It is observed that the FE model is accurate at replicating the peak impact force during empty container impact. The impact simulations of the half loaded and fully loaded container with rigidly attached NSM uniformly distributed over the entire wooden floor were conducted at different impact velocities. The results indicate that increase in payload mass leads to an increase in peak impact force during relatively low impact velocities. However, the peak impact force tends to reach a limit during high impact velocities. This is because the high impact velocity and payload mass contribute to large plastic deformations of the axial impacting members of the container and therefore the damage, in turn, leads to significant kinetic impact energy dissipation. The maximum peak impact force from one bottom and two
bottom corner impact of a loaded container with velocities up to 6 m/s were 884 kN and 1850 kN, respectively. Figure 5.19 also compares the simulation results with the estimated values from the 1D model. It is found that the 1D model provides an accurate estimation for the empty container. Peak impact force due to half loaded and fully loaded container impact is estimated accurately during low impact velocities while for high impact velocities it can be overestimated. This is because the 1D model conservatively assumes the NSM distributed along the length of the impacting axial member while the NSM in the simulation is distributed over the floor system.

**Figure 5.19.** Peak impact force from empty and loaded shipping container with NSM case 3 at different velocities
Impact duration from impact of empty and loaded container with NSM case 3 are shown in Figure 5.20. Comparison of the simulation results and experimental data for empty container indicates a good agreement. The impact duration of an empty and loaded container always increases with the impact velocity. The results also reveal that an increase in payload mass leads to an increase in the impact duration of the loaded container with rigidly attached NSM. Figure 5.20 also shows that the impact durations estimated from the 1D model agree reasonably well with the simulation results.

![Figure 5.20](image)

**Figure 5.20.** Impact duration for empty and loaded shipping container with NSM case 3 at different impact velocities
Comparison of the impulse versus impact velocity for empty and loaded container is shown in Figure 5.21. A good agreement between test data and simulation results is observed during empty container impact. It is also observed that the impulse increases linearly with the impact velocity during relatively high impact velocity. The impulse of single corner impact of a container is always less than the impulse of the two bottom corner case. This can be attributed to the fact that during single corner impact the center of the container mass continues to have a forward velocity when the container separates from the load cell due to twisting of the container. Moreover, the results are compared with the estimated impulse from the 1D model. It should be noted that the dashed lines presented in Figure 5.21 are based on the coefficient of restitution of 1.0 ($e = 1.0$); this results in a good approximation of impulse during elastic impact of a container, but it also leads to an overestimated impulse during high impact velocities.

![Graph showing impulse versus impact velocity for empty and loaded shipping container with NSM case 3](image)

**Figure 5.21.** Impulse versus impact velocity for empty and loaded shipping container with NSM case 3.
5.6. Discussion of results

In previous section, the peak impact force, impact duration, and impulse of the loaded shipping container with three different types of NSM were presented. The experimental and simulation results were compared to the estimated values from the simplified 1D model. In this section, the impact force-time histories from FE analysis results are compared with the proposed idealized force-time history outlined in Figure 5.2. Also, the dynamic structural response to the simulated and idealized force-time history is evaluated herein.

5.6.1. Impact force-time history comparison

To compare the shape of the impact force-time histories the primary peak impact force and primary impact duration from FE simulations of the loaded shipping container have been nondimensionalized by the estimated peak impact force [Eq. (5.2)] and impact duration [Eq.(5.3) for NSM cases 1 and 2 and Eq. (5.4) for NSM case 3]. Nondimensional force-time histories for loaded container impact simulations are presented in Figure 5.22 for both elastic and inelastic impact; 28,182 kg NSM case1, 2177 kg NSM case 2, and 14,091 kg NSM case 3 are considered. Comparison of primary pulse force between elastic and inelastic response indicates that the nondimensional rise time decreases as the impact velocity increases for each loaded container impact case. The short rise time observed in the loaded container inelastic response during high impact velocity is well represented by a sudden jump in the proposed rectangular pulse. The primary peak impact force is also accurately estimated by the proposed model for all
It also can be seen that the proposed model provides an adequate estimate for primary impact duration. For NSM case 1, the secondary impact duration is well estimated by the 1D model. It is observed that multiple impact force spikes occur during the secondary impact duration. The comparison shows that the average of the secondary pulse forces for NSM case 1 is well estimated by the secondary peak force from the 1D model [Eq. (5.6) case1]. For NSM case 2, the secondary peak impact force is underestimated by the 1D model, but the estimated secondary impulse values are always conservative, as illustrated previously in Figure 5.18. The secondary force spike(s) can also be observed from NSM case 2 simulations. It is found that each force spike from NSM cases 1 and 2 has almost the same duration as the primary pulse force.
Figure 5.22. Nondimensional impact force-time histories for elastic and inelastic axial impact of the loaded shipping container with NSM cases 1, 2 and 3

5.6.2. Dynamic response of the structural members

The force-time histories due to axial debris impacts exhibit that rise time and impact duration can be short in comparison with the natural period of common load-bearing structural members. Consequently, it is necessary to consider the dynamic effects when defining the design structural demands. The equivalent static force and corresponding dynamic response factor are determined using the simulated impact load histories (including primary and secondary pulses) and the estimated idealized primary load histories. The results are compared to assess the conservatism of the proposed 1D model for different debris impact scenarios. Newmark’s linear acceleration method was used to determine the response of an undamped linear SDOF system with a natural period $T_n$ to elastic and inelastic impact force-time histories for each impact case, as shown in Figure 5.22. The dynamic response factor $R_d$ (i.e., the ratio of maximum response of the SDOF system to the static displacement from the peak force) versus the duration ratio $t_p/T_n$ and $t_d/T_n$ for loaded container impact forces of equal amplitude is presented in Figures 5.23 – 5.25. The value of $t_p$ is the primary impact duration for NSM cases 1 and 2 [Eq.(5.3)] and
the value of \( t_d \) is the impact duration for NSM case 3 [Eq. (5.4)], as illustrated in Figure 5.2. The \( R_d \) factors for simulated loaded container impact forces were compared to the \( R_d \) for a rectangular pulse force corresponding to the idealized primary pulse force. Figures 5.23 and 5.24 show the \( R_d \) values versus \( t_p/T_n \) for loaded container with NSM cases 1 and 2, respectively. The comparison revealed that the dynamic response of the structural members from the impact model time history is always conservative for \( t_p/T_n \geq 1 \). Results also indicate that for non-rigidly attached NSM the 1D model may underestimate the structural response when \( 0.25 < t_p/T_n < 1 \). The maximum value of \( R_d \) for NSM cases 1 and 2 were 4.7 and 2.8, respectively, while the 1D model provides the maximum value of 2 for \( R_d \). This is because the multiple secondary force spikes each with the duration equal to \( t_p \) lead to resonance of the structure with \( T_n = 2t_p \) (i.e., when the excitation frequency is equal to the structural frequency). Figure 5.25 illustrates the \( R_d \) values for a loaded container with rigidly attached NSM. It can be seen that the proposed rectangular pulse force from the 1D model leads to a conservative \( R_d \) value for all impact cases. To specify the debris impact design force, an equivalent static force can be determined by multiplying \( R_d \) (from the rectangular pulse model) and \( F \) from Eq. (5.2). Moreover, the results are compared with the dynamic response factor from ASCE 7-10 flood chapter commentary (ASCE 2010), as shown in Figures 5.23-5.25. The comparisons imply that the \( R_d \) factor in ASCE 7-10 design provision (which is based on half-sine pulse force) is unconservative except for elastic impact cases with duration ratio larger than 0.75.
Figure 5.23. Response spectra for fully loaded shipping container impact forces of equal amplitude (NSM case 1)

Figure 5.24. Response spectra for 8% loaded shipping container impact forces of equal amplitude (NSM case 2)
Figure 5.25. Response spectra for half-loaded shipping container impact forces of equal amplitude (NSM case 3)

5.7. Conclusions

A series of full-scale experiments on an empty and loaded shipping container with different types of payload was conducted. A three-dimensional nonlinear dynamic FE model of the shipping container with non-structural mass (NSM) was developed and validated with results from the full-scale impact experiments. A series of loaded container impact analyses with impact velocities up to 8 m/s were conducted. The simulations consisted of non-rigidly and rigidly attached NSM to study the effect of NSM on container impact demands. The experimental and simulation results show that for non-rigidly attached NSM secondary pulse forces occur and the primary peak impact force and duration are not affected by the payload mass. It is also found that for rigidly attached NSM the peak impact force is influenced by the payload mass but secondary impacts do not occur. In all cases the maximum impact force is limited by the inelastic
response of the container that occurs at elevated impact velocities, however, this occurs earlier for rigidly attached NSM.

A simplified 1D model is proposed to estimate the axial impact demands generated from containers with NSM. The proposed approach considered three levels of connectivity between the NSM and the structure of the container: “sliding” mass, “tied” mass and “rigidly attached” mass. The FE simulations and experimental data were used to validate the proposed model. It was found that the simplified model allows for an accurate prediction of the peak impact force for all three NSM cases. The proposed approach also provides an adequate approximation for determination of primary and secondary impact durations.

Analysis of a SDOF structural model subject to the loaded container impact demands indicates that the dynamic response factor computed using the 1D model provides a conservative equivalent static force for most impact cases. The analysis results also revealed that for $0.25 < t_p/T_n < 1$, the non-rigidly attached NSM may impose significant additional impact demand on the structural member due to resonance. Additionally, results indicate that the dynamic response factor provided by ASCE 7-10 flood chapter commentary is unconservative for loaded container impacts.

The results of this study can also be used for characterization of the axial impact of other debris systems with contents.
CHAPTER 6

Study of Demands Resulting from Transverse Impact of Debris

6.1. Introduction

In previous chapters, axial impact of debris was assessed to determine the debris impact demands in worst-case scenarios. However, site surveys demonstrated that a transverse impact of debris (i.e., impact with a transverse member of debris) is more likely to occur during tsunamis or hurricane storm surges.

This chapter presents an experimental program in which full-scale in-air transverse impact tests were carried out with a shipping container, steel solid bar and hollow tube sections. The primary goal was to quantify the behavior of debris under transverse impact and to develop a simple model to estimate the peak force and duration during transverse debris impact events. The experimental data was used to validate the simplified model.

6.2. Simplified models for transverse debris impact

A simplified model is used to estimate accurately the impact demands of debris under elastic transverse impacts. It is assumed that the debris with total mass $m_d$ strikes a rigid structure with the impact velocity $v$ and the response of the debris is governed by bending.
A simplified single-degree-of-freedom (SDOF) dynamic model with a single point mass is utilized. The proposed model estimates peak impact force and impact duration of the impact event. The debris is modeled as a nonuniform elastic bar with distributed mass and cross-sectional area along its length. Figure 6.1 shows a schematic of the bar model before and after impact. $L$ is total length of the bar; $m$ is the mass per unit length; $E$ and $I$ are the elastic modulus and second moment of area about the axis of bending, respectively; $u$ denotes the lateral displacement of the debris and $\ddot{u}$ its acceleration during impact; and $U(t)$ is the generalized coordinate. The displacement of the bar can be expressed by $u(x, t) = U(t)\psi(x)$, where $\psi(x)$ is the shape function. The generalized SDF system (Chopra 2007) of the transverse bar impact model can be developed by the principle of virtual displacements. The external virtual work $W_E$ due to the acceleration $\ddot{u}(x, t)$ acting through the virtual displacements $\delta u(x)$ is

$$W_E = \int_0^L -m(x)\ddot{u}(x, t)\delta u(x) \, dx$$  \hspace{1cm} (6.1)$$

The internal virtual work $W_I$ due to the bending moment acting through the virtual curvature $\delta u''(x) = \delta[\partial^2 u/\partial x^2]$ is

$$W_I = \int_0^L EI(x)u''(x, t)\delta u''(x) \, dx$$  \hspace{1cm} (6.2)$$

By equating external virtual work with internal virtual work and defining displacements $u(x, t)$ in terms of generalized coordinate $U(t)$, the equation of motion for
the generalized system is $M_e \ddot{U} + K_e U = 0$, where $M_e$ and $K_e$ are equivalent mass and equivalent stiffness, respectively:

\[
M_e = \int_0^L m(x)[\psi(x)]^2 \, dx \tag{6.3}
\]

\[
K_e = \int_0^L EI(x)[\psi''(x)]^2 \, dx \tag{6.4}
\]

The SDF impact model is shown in Figure 6.1 Solution of the equation of motion with initial velocity (i.e. impact velocity) $v$ provides the impact force $F(t)$ with a half-sine pulse shape.

\[
F(t) = K_e U(t) = v\sqrt{K_e M_e} \sin \left( t\sqrt{K_e / M_e} \right) \tag{6.5}
\]

Therefore, the peak impact force $F_p$ is

\[
F_p = v\sqrt{K_e M_e} \tag{6.6}
\]

The impact duration $t_d$ is the duration of the half-sine pulse force and is given by

\[
t_d = \pi \sqrt{\frac{M_e}{K_e}} \tag{6.7}
\]
Full-scale experiments were conducted on a shipping container, steel solid bar and hollow tube sections to investigate the generated impact force and duration during transverse impact.

The impact setup illustrated in Chapter 2 was utilized to conduct transverse impact experiments. For each test series the location of the load cell was adjusted to ensure impact on the middle of a transverse member. For shipping container test series, the corner post and bottom beam components of the container were chosen as transverse members (see Figure 6.2). To further study the behavior of debris under transverse impact, the shipping container was modified by attaching pinned supports to the top and bottom of the corner post. Pinned supports consisted of four steel plates with a total mass of 21 kg. A 2.6 m steel tube and solid bar were used as a simplified transverse member of
the container with pinned supports at both ends, as shown in Figure 6.2. The steel solid bar was a hot rolled square 5.1 × 5.1 cm (2 × 2 in.) and had a total mass of 55.3 kg. The steel tube was square tubing 5.1 × 5.1 × 0.17 cm (2 × 2 × 1/16 in.) and had a total mass of 6.8 kg. The steel tube and solid bar conform to ASTM A500 (Grade B) and ASTM A588, respectively. The modulus of elasticity was taken to be 207 GPa. The sectional details of the transverse members are illustrated in Figure 6.3.

Table 6.1 summarizes the test matrix for the transverse debris impact. The impact velocity for each elastic test series was increased up to yield of the transverse member. In addition to the elastic test series, impact trials with relatively high impact velocities were performed to investigate the inelastic behavior of the debris under transverse impact. Inelastic damage to the transverse members is shown in Figure 6.4.

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Target transverse member</th>
<th>Impact location</th>
<th>Debris response</th>
<th>Speed range (m/s)</th>
<th>Number of trials</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Container bottom beam</td>
<td>Midspan</td>
<td>Elastic</td>
<td>0.46-0.96</td>
<td>7</td>
</tr>
<tr>
<td>C2</td>
<td>Container corner post</td>
<td>Midspan</td>
<td>Elastic</td>
<td>0.35-0.95</td>
<td>8</td>
</tr>
<tr>
<td>C3</td>
<td>Container bottom beam</td>
<td>Midspan</td>
<td>Inelastic</td>
<td>3.78</td>
<td>1</td>
</tr>
<tr>
<td>C4</td>
<td>Container corner post</td>
<td>Midspan</td>
<td>Inelastic</td>
<td>3.91</td>
<td>1</td>
</tr>
<tr>
<td>S1</td>
<td>Steel solid bar</td>
<td>Midspan</td>
<td>Elastic</td>
<td>0.07-0.53</td>
<td>12</td>
</tr>
<tr>
<td>S2</td>
<td>Steel solid bar</td>
<td>Midspan</td>
<td>Inelastic</td>
<td>1.89</td>
<td>1</td>
</tr>
<tr>
<td>H1</td>
<td>Steel hollow tube</td>
<td>Midspan</td>
<td>Elastic</td>
<td>0.06-0.25</td>
<td>9</td>
</tr>
<tr>
<td>H2</td>
<td>Steel hollow tube</td>
<td>Midspan</td>
<td>Inelastic</td>
<td>0.48</td>
<td>1</td>
</tr>
</tbody>
</table>
**Figure 6.2.** Transverse debris impact test setup

**Figure 6.3.** Section details of shipping container components and simplified transverse members

(Units: cm)
Figure 6.4. Inelastic damage due to transverse impact: hollow tube section (H2), solid bar section (S2), container bottom beam (C3), container corner post (C4). Dashed lines represent the undamaged position of members

6.4. Experimental results

In this section, results of the experimental tests for transverse impact of the shipping container members (bottom beam and corner post) and simplified members (tube and solid bar sections) are presented. For each trial, impact velocity, force and duration from the load cell, and strain of the debris were measured. Impact force is determined from the measured response of the load cell.

6.4.1. Transverse impact of shipping container members

The measured shipping container impact force-time histories for both corner post and bottom beam impact cases are shown in Figure 6.5. The elastic and inelastic responses of the container with impact velocities of 1 m/s and 4 m/s, respectively, are presented. It can be seen that the rise time significantly decreases during inelastic response with a relatively high impact velocity.
Figure 6.5. Measured force-time histories for shipping container with impact velocities of approximately 1 m/s and 4 m/s for elastic and inelastic impact, respectively.

The measured relationship between peak impact force and impact velocity for axial and transverse impact of the shipping container are presented in Figure 6.6. The results indicate that the peak force varies linearly with the velocity during elastic response with relatively low impact velocities. For the higher impact velocities the inelastic response of the container leads to a significant reduction in peak impact force values. It is also found that the axial bottom corner impact represents the worst cases scenario for single point impact of the shipping container. Additionally, the experimental results are compared with the estimated values from existing design guidelines. It can be seen that FEMA P646 (2012) provides overly conservative values especially for relatively high impact velocities while ASCE-7 (2010) underestimates the peak impact force values for all single point elastic impact cases.
Figure 6.6. Measured shipping container peak impact force due to axial and transverse impact

The measured impact duration due to container axial and transverse impact are shown in Figure 6.7. The impact duration remains constant during elastic impact, whereas the impact duration tends to increase with impact velocity during inelastic impact. The transverse impact results in a higher impact duration than the axial impact. Also, the results show that the impact duration suggested by ASCE 7 (2010) is higher than the impact duration due to shipping container single point impact.

Figure 6.7. Measured impact duration of shipping container resulting from axial and transverse impact
6.4.2. Transverse impact of simplified members

Figure 6.8 shows the peak impact force for solid bar and hollow tube sections transverse impact under both elastic and inelastic response. Note that the strain data indicated that the members were yielded at midspan with impact velocity of approximately 0.5 m/s and 0.25 m/s for solid bar and hollow tube, respectively. Also, the inelastic damage from experiments S2 and H2 was depicted in Figure 6.4. However, the peak impact force during inelastic response does not reduce, as shown in Figure 6.8. This is due to a development of membrane tension forces during large deformation of the transverse member with pin-ends.

![Figure 6.8. Peak impact force versus impact velocity for impact of simplified transverse members](image)

Figure 6.9 shows the impact duration for impact of simplified transverse members under elastic and inelastic response. It is shown that the impact duration remains constant for elastic impacts and does not increase for inelastic impacts due to tension membrane development.
Figure 6.9. Impact duration versus impact velocity for impact of simplified transverse members

6.5. Transverse debris impact demands estimation

The SDOF impact model presented in section 6.2 is used to estimate the debris impact demands during transverse impact. The estimated values are compared to the experimental data to validate the SDOF impact model.

Since the main axial members of the container are located at the ends of the transverse members (i.e., corner post and bottom beam components), large proportion of the inertia during impact will be applied at the ends of the transverse member. Therefore, to obtain the equivalent mass for impact of the transverse component of the container, it is assumed that the total mass of the other components is lumped at both ends of the transverse component. In this case, the equivalent mass ((6.3) can be approximated by using only the total mass of the debris ($m_d$). Figure 6.10 shows the error of approximated effective mass for a transverse member with two different boundary conditions. $m_t$ is the mass of the transverse component and $m_s$ is the total mass of the supports including other components of the debris (lumped masses), as shown in Figure 6.10. It is shown that the
effective mass error for all test series presented in this paper is less than 2%. Therefore, the total mass of the debris ($m_{d}$) is used as an effective mass herein.

![Diagram showing effective mass error for transverse member with lumped masses at the ends](image)

**Figure 6.10.** Approximation of effective mass for transverse member with lumped masses at the ends

Shape function is assumed to be determined from deflection of the transverse member due to concentrated static load at the impact location. Thus, $K_e = 48EI/L^3$ for simply supports and $K_e = 192EI/L^3$ for fixed end supports are used for SDOF impact model.

The simply supported boundary conditions are assumed for the container corner post. Due to the fact that the container bottom beam ends are stiffened by steel plates, boundary conditions are assumed to be fixed supported for bottom beam member. Boundary conditions of the simplified transverse members are assumed to be simply supported during elastic impact. Table 6.2 lists the support boundary conditions for each
transverse member and the corresponding equivalent mass and stiffness of the SDOF impact model.

**Table 6.2. Equivalent mass and stiffness of the SDOF impact model for transverse debris impact estimations**

<table>
<thead>
<tr>
<th>Transverse member</th>
<th>Support conditions</th>
<th>$L$ (m)</th>
<th>$I$ (cm$^4$)</th>
<th>Equivalent mass, $M_e$ (kg)</th>
<th>Equivalent stiffness, $K_e$ (MN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Container bottom beam</td>
<td>Fixed ends</td>
<td>2.12</td>
<td>335.3</td>
<td>2300</td>
<td>13.96</td>
</tr>
<tr>
<td>Container corner post</td>
<td>Pinned ends</td>
<td>2.30</td>
<td>1264</td>
<td>2300</td>
<td>10.33</td>
</tr>
<tr>
<td>Modified container - solid bar</td>
<td>Pinned ends</td>
<td>2.60</td>
<td>55.4</td>
<td>2376</td>
<td>0.311</td>
</tr>
<tr>
<td>Modified container - hollow tube</td>
<td>Pinned ends</td>
<td>2.60</td>
<td>13.1</td>
<td>2327</td>
<td>0.074</td>
</tr>
</tbody>
</table>

**6.5.1. Impact force-time history**

The measured peak impact forces and impact durations have been nondimensionalized by the peak force and duration from the SDOF impact model [Eqs. (6.6) and (6.7), respectively]. Nondimensionalized impact force-time histories for representative elastic trials are presented in Figure 6.11 for each impact case over a range of impact velocities. The peak impact force occurred approximately at the middle of the impact duration for all test series. The approximate shape of the force time history was half-sine. It is shown that the SDOF impact model provides accurate results for simplified transverse members and estimated results are in good agreement with the transverse container impact results.
Figure 6.11. Nondimensional load cells histories resulting from transverse impact: (a) shipping container bottom beam; (b) shipping container corner post; (c) hollow tube section; (d) solid bar section.

6.5.2. Peak impact force and impact duration

The nondimensional measured peak impact force and impact duration (i.e., the ratio of measured value to estimated value) for the transverse impact of the container are shown in Figure 6.12. The results indicate that the SDOF impact model provides a reasonable approximation for peak force and duration.

Figure 6.12. Nondimensionalized measured peak impact force and impact duration versus impact velocity for transverse shipping container impact tests.
The nondimensional measured values of peak impact force and impact duration at varying velocities for simplified transverse members are shown in Figure 6.13. It is shown that the experimental results agree well with the estimated values from SDOF impact model.

![Figure 6.13. Nondimensionalized measured peak impact force and impact duration versus impact velocity for transverse impact of simplified members](image)

6.6. Dynamic response of the structural members

In order to design a structure for dynamic impact demands the equivalent static forces need to be determined. The equivalent static force and corresponding dynamic response factor are determined using the measured impact load histories and the estimated load histories. The results are compared to assess the conservatism of the SDOF model for transverse shipping container impact under elastic response. Newmark’s linear acceleration method (Chopra 2007) was used to determine the response of an undamped linear SDOF system with a natural period $T_n$ to an average force-time history for each
transverse container impact case. For a given elastic impact case, the average force-time history was determined as follows. Force-time histories were computed for impacts between 0.5 m/s to 1 m/s, and the time duration for each was normalized. These curves were then averaged to obtain the average force-time history for normalized time. The response of the SDOF system was then obtained for this average force history applied over the average simulated impact duration. The dynamic response factor $R_d$ (i.e., the ratio of maximum response of the SDOF system to the static displacement from the peak force) versus the impact duration to $T_n$ ratio for elastic and inelastic transverse container impact forces of equal amplitude is presented in Figure 6.14. The $R_d$ factors for measured shipping container impact forces were compared to the $R_d$ for a half-sine pulse force corresponding to the SDOF impact model. The comparison revealed that the dynamic response of the structural members from the impact model time history is in good agreement with the dynamic response from experimental data. The results also indicated that the dynamic response for inelastic impact cases is higher than that for elastic impact cases. This is due to the short rise time for inelastic container impact cases. To specify the debris impact design force, an equivalent static force can be determined by multiplying $R_d$ (from the half-sine pulse model) and $F$ from Eq. (6.6). Moreover, the results are compared with the dynamic response factor from ASCE 7 (2010) flood chapter commentary, as shown in Figure 6.14. The comparisons imply that the $R_d$ factor in ASCE 7-10 design provision is conservative for container elastic transverse impact cases. However, for the container inelastic impacts ASCE 7-10 provides unconservative values of $R_d$ factor.
Figure 6.14. Response spectra for transverse shipping container impact forces of equal amplitude

6.7. Conclusions

In this chapter, a series of full-scale impact experiments were conducted on a shipping container, steel solid bar and hollow tube to investigate the transverse debris impact demands. A simplified SDOF impact model is proposed to estimate impact force and duration of the elastic transverse debris impact events. The experimental results are used to validate the SDOF impact model. It is found that the SDOF impact model provides an adequate approximation for determination of the peak impact force and duration during elastic transverse debris impacts.

Analysis of a SDOF structural model subject to the measured shipping container impact demands indicates that the dynamic response factor provided by ASCE 7 is unconservative for inelastic impact cases.
CHAPTER 7

Summary and Conclusions

The goal of this dissertation is to obtain a better understanding of the demands resulting from debris impact on structures and to develop simplified model to estimate accurately the debris impact demands. The results of this study contribute to improvement of the current approaches available in design guidelines to determine debris impact demands in floods, tsunamis, and hurricane storm surges.

A series of full-scale impact experiments were conducted on a wood utility pole, steel tube, solid bar, and shipping container to quantify demands due to the axial and transverse impact of the debris under elastic and inelastic responses. A loaded shipping container with different types of payload restraint systems was considered to study the effect of nonstructural mass on the debris impact demands. All experimental data are submitted to and archived in the NEES Data Repository and are available on the web. The details of the experimental data can be found at: https://nees.org/warehouse/experiments/942.

Three-dimensional nonlinear dynamic FE model of a 20-ft shipping container with contents was developed. The FE models are validated against the full-scale impact experiments. The effect of inelasticity on impact force and duration are evaluated through the parametric study.
Impact models are developed to estimate the axial and transverse impact demands from debris under elastic and inelastic response. An approach is developed to account for the magnitude and restraint system of the contents of the debris on impact demands. The experimental and simulation results were used to validate the proposed models. It is found that the impact models allow for an accurate prediction of the demands from debris. The proposed models can be used in code provisions to estimate both the impact force and duration demands.

It is assumed that the debris impact event and structural response are decoupled in the design approach presented in this work. The interaction between the structural member and debris during impact event can also be considered in the model for future research on this topic.
References


Dassault Systems, Abaqus Unified FEA software, Ver. 6.13, Dassault Systems Simulia Corp, Providence, RI, USA.


156


Vita

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