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Estimation of demands resulting from inelastic axial impact of steel debris

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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 inelastic response of the debris and to develop a simple model that can estimate impact force and duration accurately. In previous work, a series of debris axial impact experiments were conducted at full scale under increasing impact velocities of up to 3.8 m/s. In this paper, the results are used to validate nonlinear dynamic finite element models of simplified and complex debris-types and are used to examine response under impact velocities up to 15 m/s. A simplified one-dimensional (1D) model is developed, illustrated, and validated using a simple debris-type consisting of a steel tube under axial impact. The model is also extended to estimate impact demands for complex debris-types such as shipping containers. This model is examined using numerical models and validated with data from full-scale impact experiments of a container. The numerical and simplified models provide accurate estimation of the axial impact demands generated under inelastic response of the debris. Results indicate that as the debris response changes from elastic to inelastic the duration of the impact event increases and the peak impact force generated reaches a limit. The maximum impact force is found to be equal to the strength of the axial members under impact. The results also 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.

1. Introduction and 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 [1–6]. 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 [3]. 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 [4]. The failed building components themselves, including steel, concrete, and wood structural components, become part of the debris field and contribute to impact events [1,6]. 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 [4]. Severe damage to steel and reinforced concrete structural members due to shipping container impact has been observed [2,3].

Current design guidelines [7–9] use simple approaches to estimate water-borne debris impact forces, but there is no consensus on the specification of the design force [10]. 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

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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 [11]. The peak impact force estimated by the impulse-momentum approach is $F = \pi m_d v/2\Delta t$ given in ASCE 7-10 [7], where m_d is the total mass of the debris, v is the impact velocity, and Δt is the time to reduce the debris velocity to zero; a value of 0.03 s is recommended for Δt based on the log impact test results. Note that Δt is half the impact duration (t_d, the time between the initial contact and the end of the contact) presented in this paper. Based on [11], FEMA P646 [9] specifies a peak impact force $F = v\sqrt{km_d}$, 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 [9]. 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 studies maximum impact forces from flood-borne woody debris were experimentally investigated and empirical formulae were proposed [11–13]. Related to vessel ‘debris’ impact, experimental and numerical studies have been conducted to define the barge impact force during barge collision with bridge piers [14–18]. Numerical investigations have been carried out to evaluate the generated forces during shipping container impact on a reinforced concrete column [19–21]. Formulae were obtained to estimate impact durations and effective contact stiffness (k) of concrete columns and shipping containers based on the simulation results. Recently, full-scale in-air axial impact tests of a wood utility pole, steel tube and shipping container have been conducted [22]. 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 [22–25]. A small-scale model of the shipping container was tested in a wave flume to investigate the effect of water on debris impact forces [23,27]; see also [26] for related experiments and simulation. The contribution of water to the debris impact demands was found to be secondary to the “pure” structural impact [23,27]. In FEMA P646 [9], 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.

This paper presents the results of impact demands from nonlinear dynamic finite element (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 [22]. 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 (1D) 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.

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 [22]. In this paper, 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. Fig. 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.

The impact force for the elastic bar model is obtained from the solution of the one-dimensional wave equation [23,24]. 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 $F = vc_e\rho A = v\sqrt{m_d k_{de}}$, in which ρ 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

$$c_p = \sqrt{\frac{\partial\sigma/\partial\varepsilon}{\rho}} \tag{1}$$

in which σ is the stress and ε is strain. The estimation of debris peak impact force using an equivalent 1D inelastic bar model is presented in Fig. 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 (σ–ε) relationship of the inelastic bar is required. Fig. 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 ΔF_i and impact velocity increment Δv_i corresponding to the segment i are computed as presented in Fig. 1. The debris peak impact force applied to the structure is given by

$$F_{i+1} = F_i + \Delta F_i \tag{2}$$

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 $k_{dp} = E_pA/L$. The impact velocity leading to an initial yielding of the bar is