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Effect of nonstructural mass on debris impact demands: Experimental and simulation studies

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ABSTRACT

Tsunamis, floods, and hurricane storm surge and waves generate debris such as shipping containers, trees, and vehicles. Impact forces imposed on buildings and bridges from such debris can lead to extensive structural damage. A reliable estimation of debris impact demands is vital for the safe design of structures against water-borne debris. The objectives of this study are to investigate the effect that supplemental non-structural mass attached to debris has on the generated impact demands and to develop a simple model that accurately estimates the peak impact force, impulse, and duration. An experimental study is carried out on a loaded shipping container subjected to in-air axial impacts. 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. The results indicate that the peak impact force is not affected by a non-rigidly attached payload mass. The experimental data and simulation results are used to develop and justify a simplified method for estimating the impact force. The simplified method is found to provide an accurate estimate of debris impact demands.

1. Introduction and background

Water-borne debris generated during extreme events such as tsunamis, hurricane storm surges, and floods can impose considerable impact forces on commercial, residential and government infrastructure. Tropical storms and hurricanes produce high winds and low pressure systems that result in an increase in water elevation along the coastline. Site surveys indicated that any buoyant or mobile object in the nearshore or onshore areas can become floating debris during tsunami and hurricane storm surge events and may lead to severe damage to buildings, vertical evacuation shelters, and port and industrial facilities in the inundation zone [1–7]. Massive objects such as large boats and vessels become adrift by the tsunami and storm surge flow due to failure of mooring systems and therefore could become a serious hazard to coastal buildings [3,4]. 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 [4]. 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 [2,3]. 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 debris without contents. 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 [8]. Numerical simulation and dynamic analysis

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of the barge impact with varying mass were 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 [9]. The density of solid elements were changed during numerical simulations to study the effect of barge mass [10,11]. These studies 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 [12]. 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 [13]. The comparison indicated that the impact force estimation from current design guidelines is unconservative for the loaded shipping container during multicorner impact cases.

Recently, full-scale in-air axial impact tests of a wood utility pole, steel tube and empty shipping container have been conducted [14]. 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 [14–17]. Additionally, an inelastic model was developed and validated by experimental and simulation results to estimate the debris impact demands [18]. The simplified models do not account for the nonstructural contents of the debris. A small-scale model of the shipping container was tested in a wave flume to investigate the effect of water on debris impact forces [15,19,20]. Unsecured steel plates were used as a payload to study the effect of contents on impact force [19,20]. It was found that the payload has no significant effect on measured peak impact force.

Prevailing design guidelines [21–23] use simple approaches for debris impact force but there is no consensus on the specification of the design force [24]. 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 SDOF spring-mass system where the stiffness of the interaction between the debris and the structure is required [25]. 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 study 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. In-water debris impact test results indicated that the effect of the fluid was negligible for design purposes [19,20], consequently the analysis approach does not consider the hydraulic effects on the impact event. Furthermore, the single object impact scenario is studied herein and the investigation of the damming effects from waterborne debris is beyond the scope of this study. 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 finite element (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.

2. Simplified analytical impact model

A general approach is developed using a simplified dynamic model to provide an accurate estimate of the debris axial impact demands. It is assumed that the target structure is rigid during the impact event. This decouples the debris impact force from the response of the impacted object which provides a conservative estimate of the demands generated. The approach accounts for the effect of the contents and its connectivity to the debris.

Previously, an equivalent one-dimensional (1D) bar model was developed and validated by experimental and simulation results for elastic and inelastic debris impact [14,18]. The debris is modeled as a uniform bar of length L, cross sectional area A, mass m, and equivalent stiffness k_d, subjected to axial impact. A schematic of the equivalent 1D bar is shown in Fig. 1. F is the impact force due to impact on a rigid structure and v is the impact velocity. For 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 is (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 ρ 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 $c_p = \sqrt{(\partial\sigma/\partial\varepsilon)/\rho}$, where σ is the stress and ε 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) [15,16]. This formulation assumes that the projectile impacts a rigid structure and responds in a uniaxial

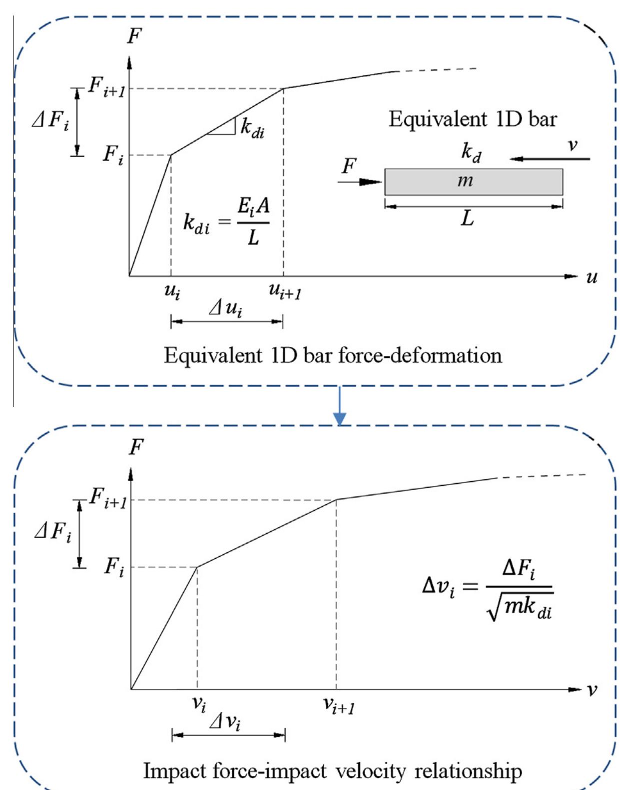

Fig. 1. Estimation of debris impact force using equivalent 1D bar model [18].