

Are Tsunami Resistant Buildings Designed with Elevated Lower Levels Safe as Evacuation Buildings?

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1. Introduction

In order to mitigate building damage, tsunami resistant building designs have been adopted where the lower level of the building is elevated by means of RC columns to allow the free flow of tsunami waves. An example of such a building is shown in Fig. 1. In this paper, the impact of tsunami water-borne massive objects on a RC building that is designed with an elevated lower level is considered.



Fig. 1. A tsunami resistant building with elevated lower level in Sri Lanka.

2. Design and analysis of the building

The building considered is a three-story school building, located in a tsunami inundation zone that can also be used for vertical evacuation in the event of a tsunami (Fig. 2). The building was analyzed and designed according to the strength design method specified in ACI 318-02 (ACI 2002) using SAP2000. Ordinary moment frame (OMF) for low seismic zone is considered for the building frame system. In this study, impact on a 2-D frame is considered using a fiber-based discretization model in OpenSEES (2006). The design details and fiber-based modeling are given in Madurapperuma (2007).

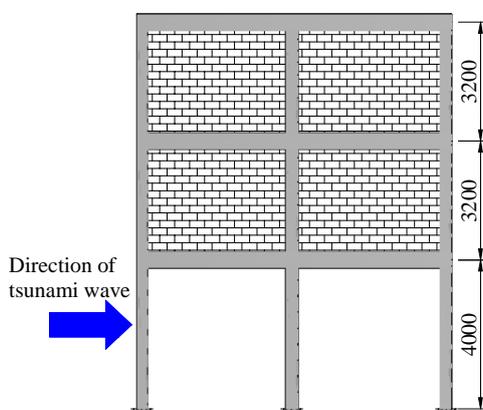


Fig. 2. Building configuration considered for impact analysis.

3. Evaluation of tsunami forces

The dominant forces that need to be considered are the hydrodynamic force and the impact force due to water-borne objects. The hydrodynamic force F_H can be evaluated from

$$F_H = \frac{1}{2} \rho C_D A u^2, \quad (1)$$

where ρ = fluid mass density, C_D = drag coefficient (2.0 for square columns), u = tsunami flow velocity, and A = wetted area of the object projected on the plane normal to the flow direction i.e., $A = hb$, in which h = flow depth and b = breadth of the object (FEMA 2000). The tsunami flow velocity is calculated from

$$u = \sqrt{2gh}, \quad (2)$$

which is based on an analytical solution of Yeh (2006), where g = gravitational acceleration. The impact force-time history is based on the impulse-momentum approach which results in the following expression for the time varying impact force F_I ,

$$\int_0^{t_i} F_I dt = \Delta(mu^{obj}) = mu, \quad (3)$$

where m = mass of the object, u^{obj} = velocity of the object and t_i = impact duration. In Eq. (3) it is assumed that velocity of the object before impact is the same as the tsunami flow velocity u and the linear momentum of the object after impact is zero. The impact duration is taken as 0.1 s and the impact force-time history is assumed to be triangular shape.

4. Numerical results

The nonlinear dynamic response of the impacted column is investigated for shipping containers impacting at the maximum tsunami flood levels of 2.0 m, 3.0 m and 4.0 m above ground level. The hydrodynamic forces and the maximum impact forces for a range of container masses are given in Madurapperuma (2007). The displacement response of the whole frame due to impact of the 1750 kg container at 2.0 m above ground level is shown in Fig. 3. The column displacement at 2.0 m above ground level attains a peak value of 18 mm after 0.0725 s and then decreases to 15 mm at the end of impact (Figs. 3(a) and 3(b)). However, a constant lateral displacement of 7 mm at the impact section and 6 mm at the roof level can be seen

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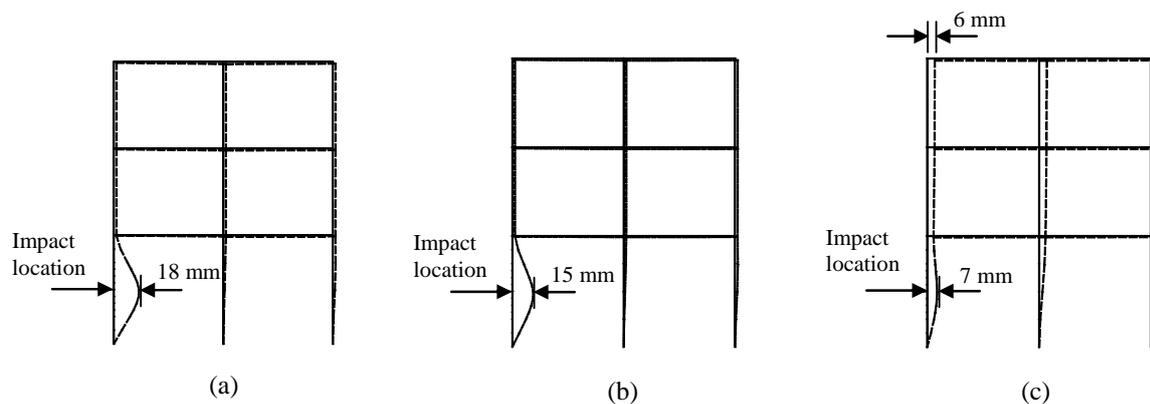


Fig. 3. Deformed shape of OMF (magnified by factor 50) when impacted by 1750 kg container at 2.0 m above GL after: (a) 0.0725 s (peak displacement), (b) 0.1 s (end of impact) and (c) 5 s.

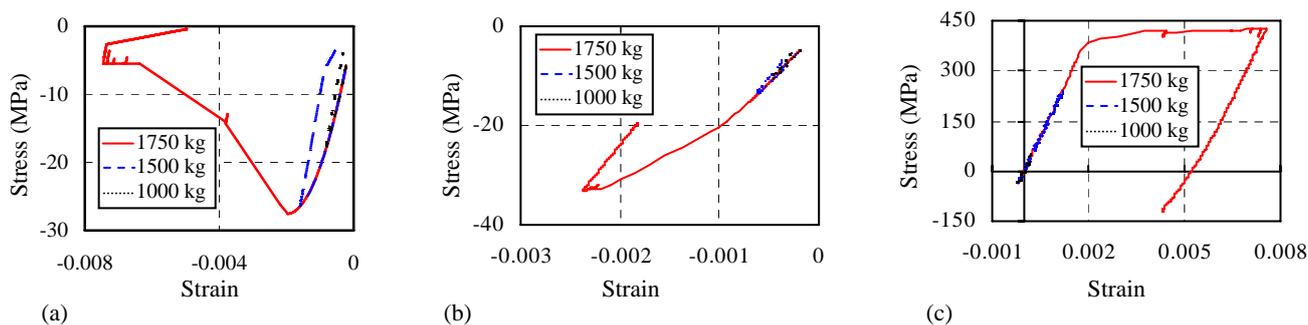


Fig. 4. Stress-strain behavior at impacted section of impacted column at 2.0 m above GL for different masses of containers: (a) cover concrete at extreme fiber in compression, (b) core concrete at extreme fiber in compression and (c) longitudinal bar in tension.

even after 5 s (Fig. 3(c)). It is expected that the spalling of cover concrete followed by the yielding and buckling of reinforcements at the impact section cause such constant displacement of the frame which is not equal to that before impact (i.e., displacement due to hydrodynamic force only). The stress-strain behavior of cover concrete, core concrete, and longitudinal reinforcement are plotted in Fig. 4, for the impact at 2.0 m above ground level for three different masses of containers. Since the cover concrete is not confined, stress in the cover concrete compression fibers exceeded the compressive strength -27.579 MPa and was almost zero at the ultimate strain of -0.005 which leads to spalling of the cover concrete due to impact of 1750 kg container (Fig. 4(a)). The stress in the core concrete compression fibers reached -32.76 MPa at a strain of -0.0023 and decreased to -19.4 MPa at a strain of -0.0018 , which shows degradation of the axial load carrying capacity due to impact of 1750 kg container (Fig. 4(b)). From Fig. 4(c) it can be seen that the longitudinal bar in tension has yielded and the maximum strain is 0.0076 which is 2.8 times the yield strain due to impact of the 1750 kg container.

5. Concluding remarks

It is found that impact at the mid section of the column is more critical than impact close to the floor level. Numerical results show that the OMF frame system is safe when impacted by the containers with a mass less than or equal to 1500 kg. But for the 1750 kg container, the impacted column suffers damage due to strength degradation. Therefore, the impact may cause extensive

damage to the critical structural members of the building according to the mass of the water-borne object. One of the impact mitigation strategies for critical buildings that may be used for evacuation purposes is strengthening the first floor using lateral bracings in the direction parallel to the tsunami flow. Another impact mitigation strategy is the construction of crash barriers to protect the building.

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