A Finite Element Approach for Structural Collapse Analysis of Buildings

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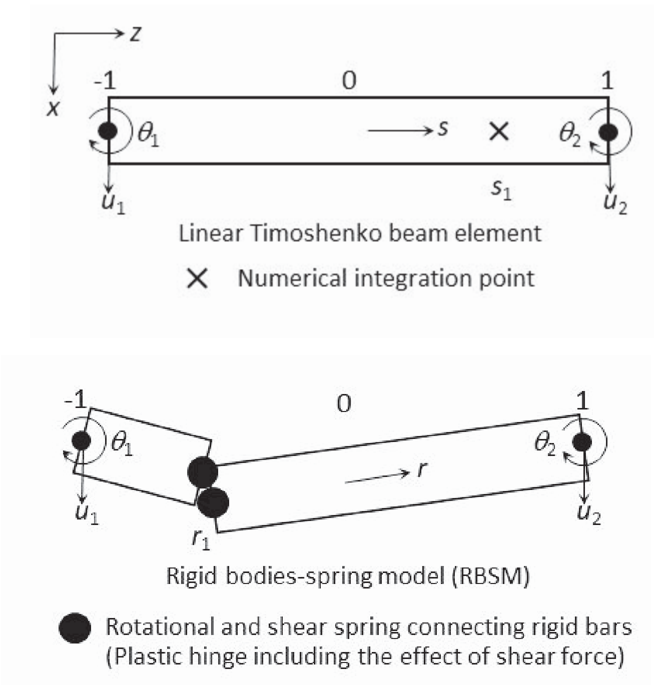
Structural designers usually do not expect a loss of structural members in buildings, but these unexpected events do occur from time to time. However, structural collapse phenomena of buildings are very difficult to reproduce in experiments. They are also difficult to be simulated numerically, since they are packed with many mechanical interactions and strong nonlinear behaviors.

The possibilities of simulations considering a loss of structural members are immeasurable, because the risk of lives often depend on the behaviors of structures after they had lost their strengths. From these strong demands, new techniques are introduced into a finite element code utilizing linear Timoshenko beam elements to cope with such discontinuous problems. The main technique adopted in the code is called the adaptively shifted integration (ASI) – Gauss technique [1]; it can drastically reduce the computational cost without losing high levels of accuracy, and, at the same time, can handle fractured sections in structural components of buildings.

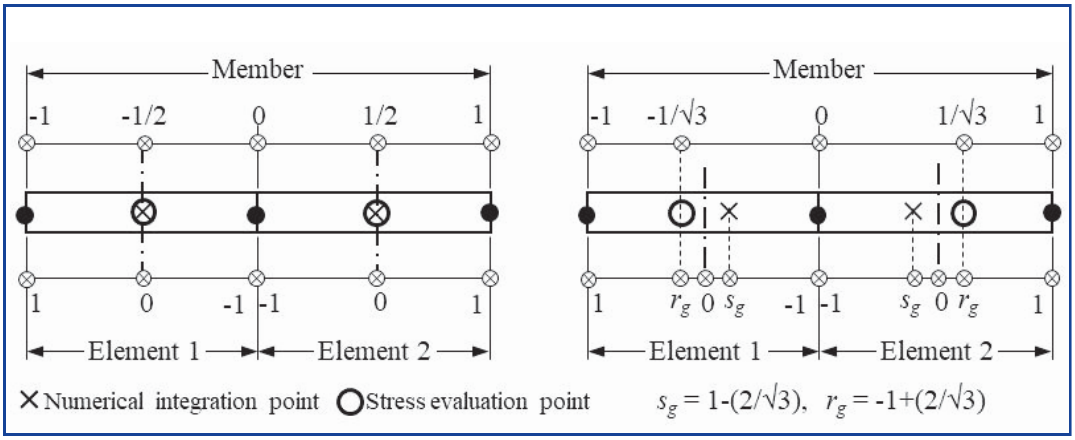
Figure 1: *Linear Timoshenko beam element and its physical equivalence to RBSM*



ASI-Gauss Technique

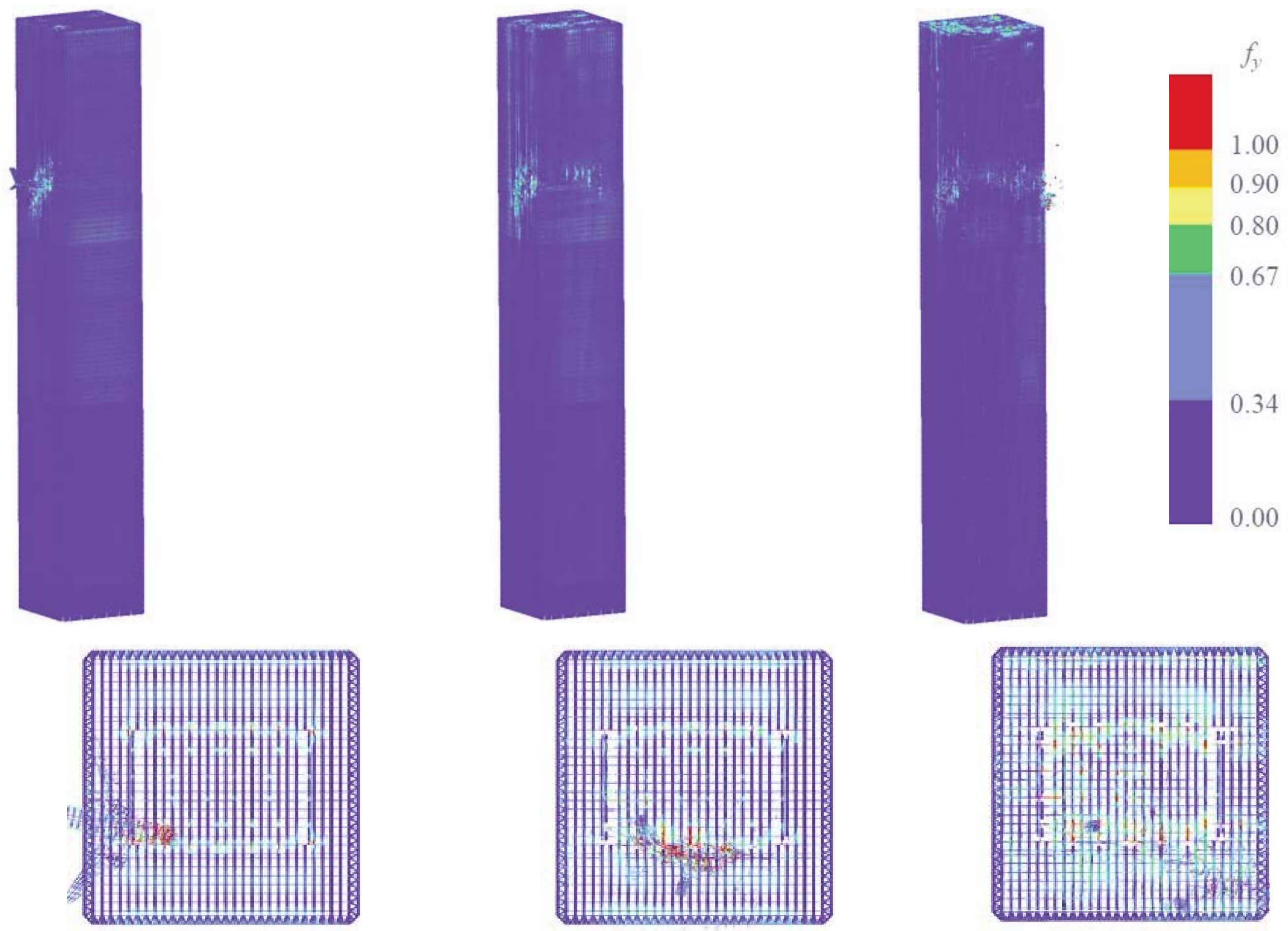
In the ASI-Gauss technique, high accuracy with small number of element subdivision is achieved by shifting numerical integration points in beam elements adaptively, when a fully plastic section is determined in the element, in order to express a plastic hinge exactly at that section in the element. This shifting is operated according to a relation between the locations of a numerical integration point and a plastic hinge [2], which is obtained by considering the equivalence conditions between the strain energy approximations of a linear Timoshenko beam element and a rigid-body-spring-model (RBSM) (*Figure 1*).

Figure 2: *Locations of the numerical integration and stress evaluation points in the elastic range*



(a) Conventional FEM　　*(b) ASI-Gauss technique*

__Figure 3:__
Bird view and upper view of the WTC 2 during aircraft collision



(a) 0.12 s after impact *(b) 0.28 s after impact* *(c) 0.56 s after impact*

When the plastic hinge is determined to be unloaded, the corresponding numerical integration point is shifted back to its initial location. By these processes, the plastic behavior of the element is simulated appropriately, and the converged solution can be obtained with a small number of elements per member. It should be noted here, that the initial location of the numerical integration point in the conventional finite element method (FEM) utilizing linear Timoshenko beam element is at the midpoint, and is always at the midpoint regardless of the present characteristic phase of the member (*Figure 2(a)*). The location is considered to be optimal for one-point integration when the entire region of the element behaves elastically. However, the bending deformations in the elastic range are less accurate when the number of elements per member is small, since the displacement functions of the finite element are defined by linear functions. Therefore, a simple means is implemented to improve the accuracy for the elastically deformed member in the ASI-Gauss technique; two consecutive elements are considered as a subset as shown in *Figure 2(b)*, and the numerical integration points of an elastically deformed member are placed such that the stress evaluation points coincide with the Gaussian integration points of the member. This means that the stresses and strains are evaluated at the Gaussian integration points of the elastically deformed members. These locations are optimal for two-point integration in the Gaussian quadrature, and the accuracy of the bending deformation defined by a cubic function is mathematically guaranteed. In this way, the ASI-Gauss technique takes advantage of two-point integration while using one-point integration per element in the actual calculations. Please refer to book [3] and papers [4-11] for further details on member fracture and elemental contact algorithms, and some verification and validation results.

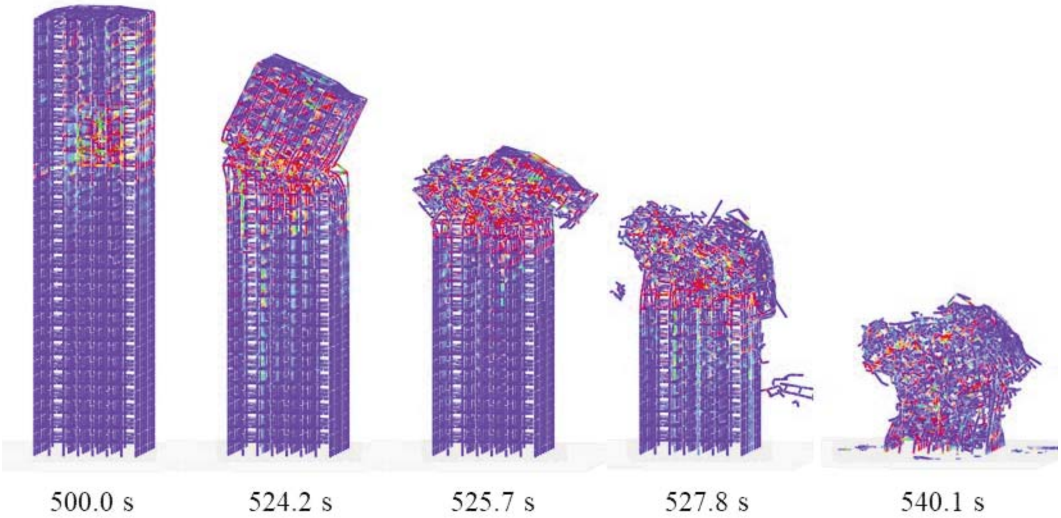


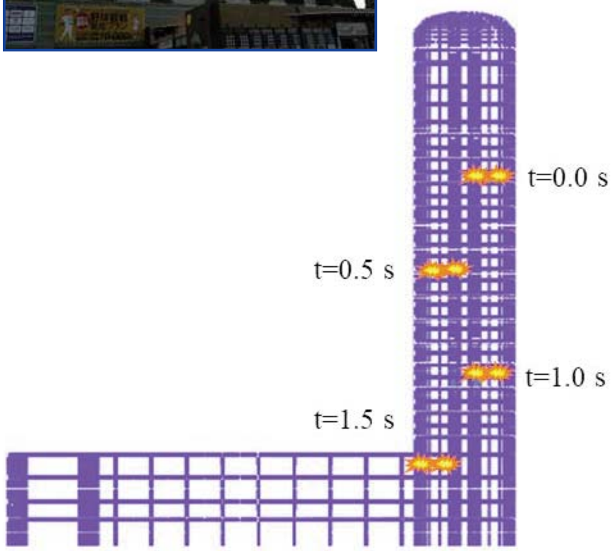
Figure 4: *Progressive collapse sequence of a high-rise tower with an outrigger truss system*

Applications

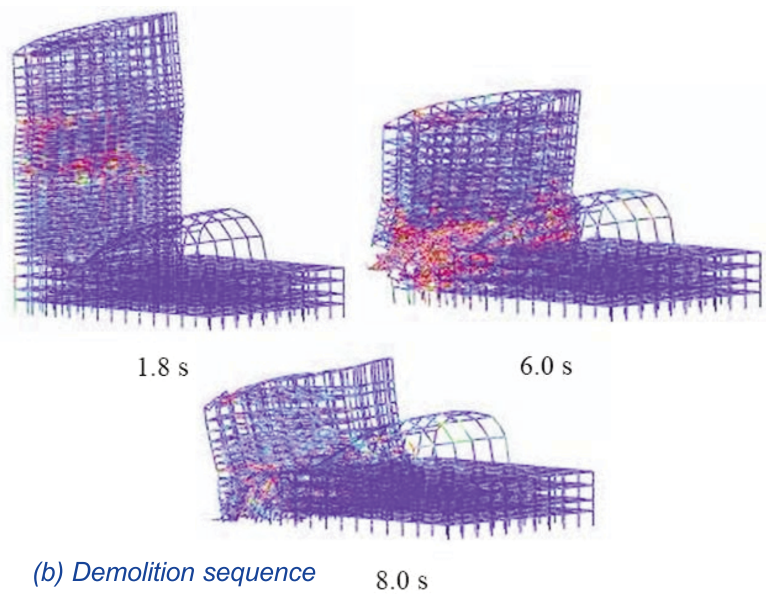
Several numerical simulations of high-rise buildings were conducted using the numerical code utilizing the ASI-Gauss technique to identify the specific structural cause of the high-speed total collapse of the World Trade Center (WTC) towers, which occurred during the 9.11 terrorist attacks. *Figure 3* shows the numerical result on full-scale aircraft impact simulation of the WTC tower 2. The colors in the figure indicate yield function values with red color indicating that the element is yielded. The simulation was conducted to examine the damage and the dynamic unloading phenomena, a so called “spring-back phenomena”, that occurred in the core columns during the impact. The spring-back phenomena might have caused the destruction of the splices between column sections, and consequently, triggered the following total collapse of the tower with a high possibility.

A fire-induced progressive collapse analysis of high-rise buildings with outrigger truss systems was carried out to qualitatively demonstrate the effects of fire

Figure 5: *Blast demolition sequence of a high-rise tower*



(a) Blast plan



(b) Demolition sequence

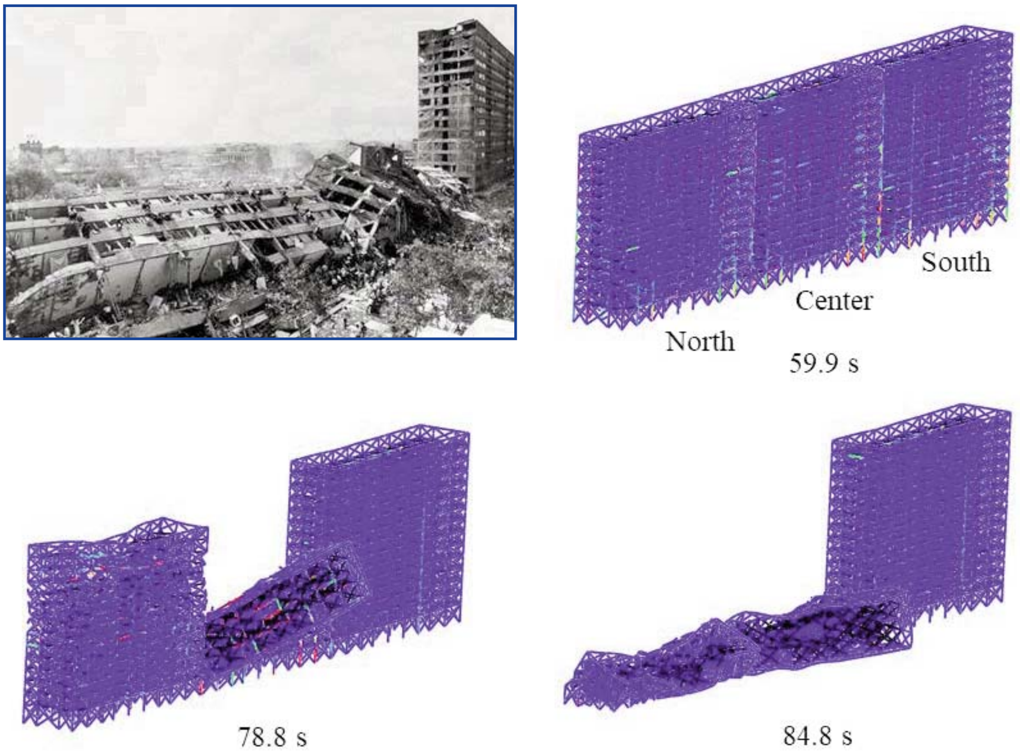
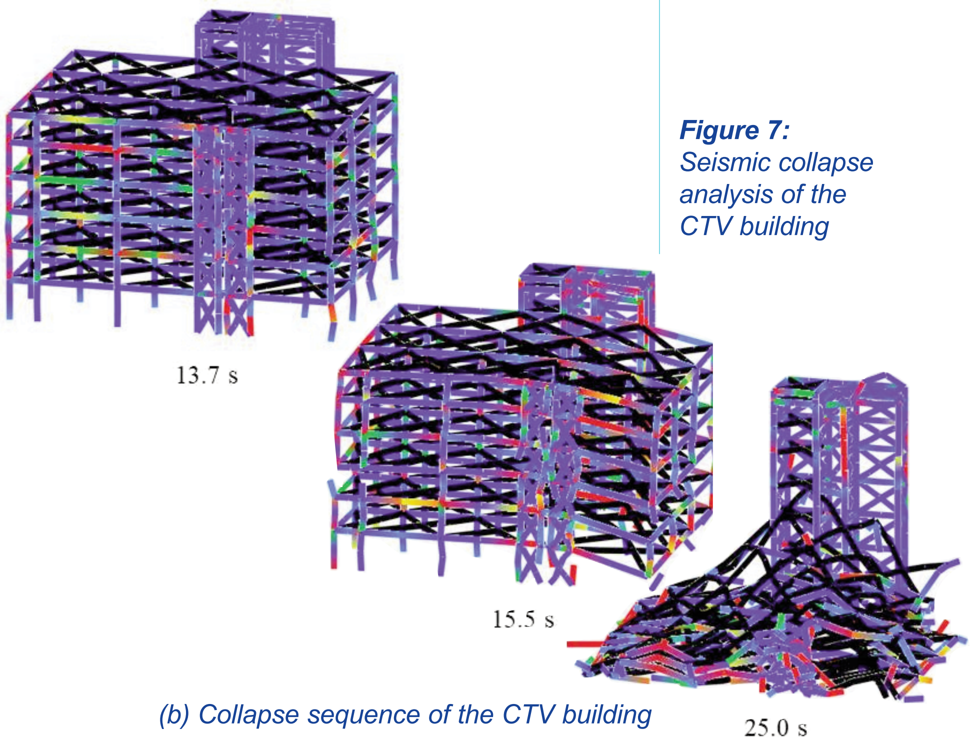


Figure 6:
Collapse behaviors of the Nuevo Leon buildings under long-period ground motion

(a) Ruins of the CTV building



(b) Collapse sequence of the CTV building

Figure 7:
Seismic collapse analysis of the CTV building

patterns and structural parameters on the progressive collapse behaviors of buildings *(Figure 4)*. The effects of fire patterns and structural parameters on the redundant strengths were surveyed by observing the collapse initiation time: the duration from the beginning of the fire until collapse initiation. It was confirmed that collapse initiation times were significantly affected by the member joint strengths if the axial force ratio was small on the condition that the fire pattern was nearly symmetrical, and the load paths to and from the outrigger truss system were sufficiently protected.

Figure 5 shows an example of blast demolition analysis conducted using the code. The building was planned to be demolished in its own wake, by carefully selecting the blast time interval and the columns of specific floors to be removed. Half of the columns on either side of the floors were removed sequentially from the

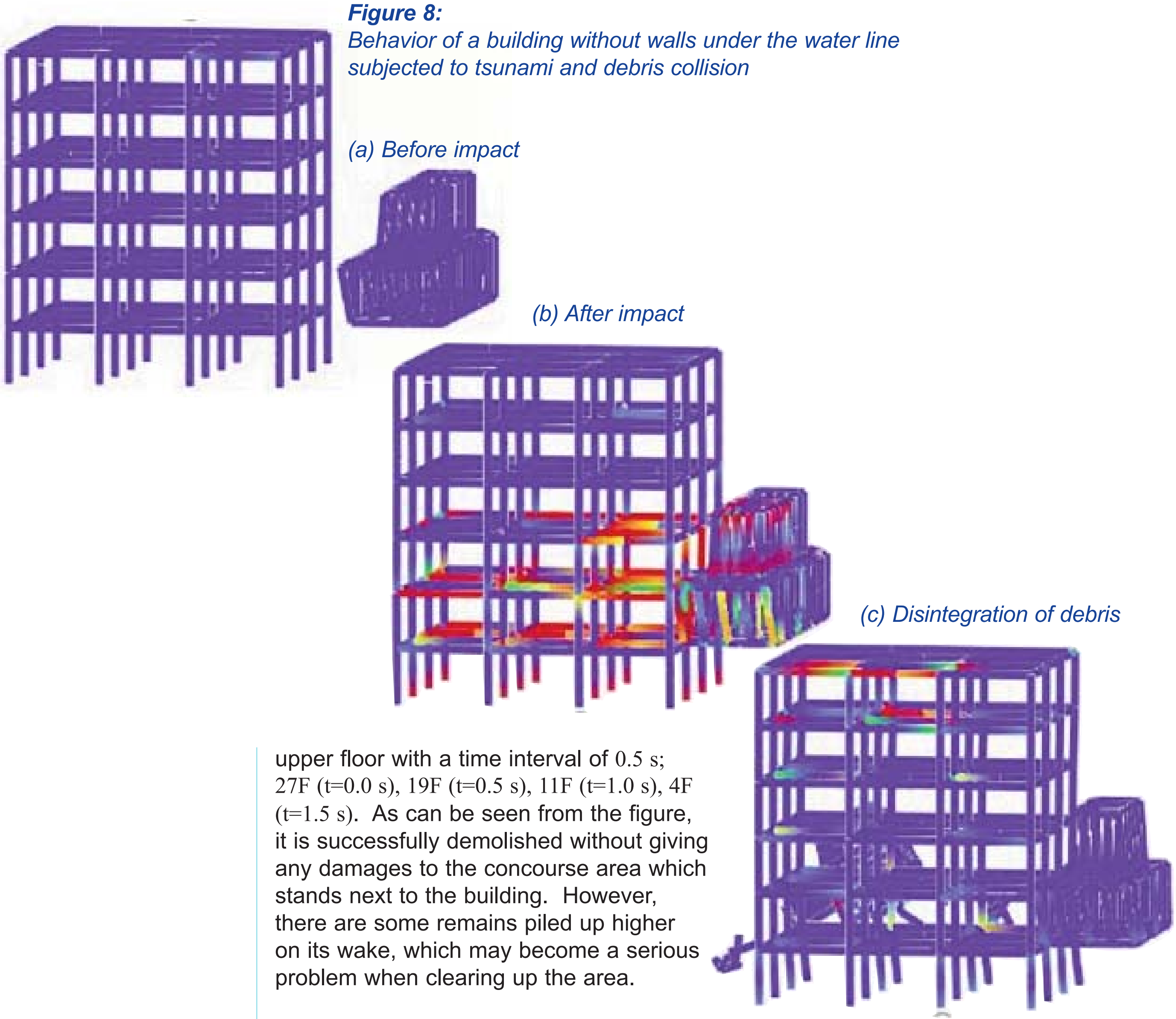


Figure 8:
Behavior of a building without walls under the water line subjected to tsunami and debris collision

(a) Before impact

(b) After impact

(c) Disintegration of debris

upper floor with a time interval of 0.5 s; 27F (t=0.0 s), 19F (t=0.5 s), 11F (t=1.0 s), 4F (t=1.5 s). As can be seen from the figure, it is successfully demolished without giving any damages to the concourse area which stands next to the building. However, there are some remains piled up higher on its wake, which may become a serious problem when clearing up the area.

A seismic pounding analysis was performed on a full model of the Nuevo Leon buildings, which consisted of three similar buildings built consecutively with narrow expansion joints between the buildings, and collapsed completely with one building remaining in the 1985 Mexican earthquake. It was aimed to understand the impact and collapse behavior of structures, built near each other, under long-period ground motion. It can be told from the numerical results that the difference of natural periods between the adjacent buildings caused by previous earthquakes may have triggered the collisions and the collapse *(Figure 6).*

An investigation was conducted on the factors that caused the collapse of the Canterbury Television (CTV) building during the Lyttelton aftershock on February 22nd, 2011, in New Zealand, which collapsed with only the north wall complex left standing. The collapse behavior with a clear twist mode vibration around the north wall complex was observed by carrying out a seismic collapse analysis *(Figure 7)*. The period of the twist mode vibration at the south-east corner of the building coincidentally matched the predominant period of the seismic wave in EW direction, which might had led to the deterioration of the columns at the location.

Figure 8 shows a behavior of a steel frame building in tsunami, which was obtained by applying seismic ground motion, fluid forces and debris collision, continuously in a single simulation. Since there are no walls under water, the building withstands the fluid force of tsunami and the following impact force applied by the debris. These results can provide information on appropriate design for tsunami refuge buildings and can also lift up a discussion to avoid the approach of large debris to such buildings.

Conclusions

The ASI-Gauss code can practically simulate the collapse behaviors of buildings with very low computational cost, and the most attractive point of this code is that it can be used in any personal computers with smaller memory resources. Although member fracture, contact and release are not considered, the developed numerical codes can be downloaded from the author's website [12, 13].

Some of the applications described here belong to real events occurred in the past. The observed data, if present, are valuable for the validation of the numerical code. One must always realize that validations are mostly important for these kinds of phenomena with strong non-linearity, because they are packed with unexpected mechanical interactions. However, it is evident that the numerical code based upon a finite element approach can provide useful information such as sectional forces acting in each member, deformation occurring in the structures, and so on, of which other methods based upon non-continuum mechanics cannot. The applicable field of the numerical code is now expanding from collapse analysis of structures to motion analysis of indoor non-structural components, and it is expected to expand further more. ●

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