Progressive Collapse of Steel Moment Frames Subjected to Vehicle Impact

Hyungoo Kang[1] and Jinkoo Kim[2]

Abstract: Structures are often subjected to vehicle collision, which can be accidental or intentional as in the case of a terrorist attack. This study investigated the performance of three-story steel moment frames with span length of 5 and 10 m subjected to vehicle collision at a first-story column using finite-element analysis software. The progressive collapse potential of the model structures was evaluated first based on the alternate path approach specified in the published guidelines. The vehicle impact analysis showed that all model structures remained stable when the speed of the vehicle was 40 km/h. However at the speeds of 80 and 120 km/h, progressive collapse occurred at both model structures after collision. The overall damages obtained from collision analysis were significantly larger than those computed based on the sudden column removal approach. **DOI: 10.1061/(ASCE)CF.1943-5509.0000665.**

Author keywords: Vehicle collision; Progressive collapse; Impact analysis; Alternate path approach; Moment frames.

Introduction

There has been a shift in terrorist modus operandi from a parked vehicle-borne improvised explosion to a penetrative attack (Cormie et al. 2009). In this regard, it is necessary to investigate the damage and collapse behavior of structures subjected to vehicle collision. Borovinsek et al. (2007) presented the results of computational simulations of road safety barrier behavior under vehicle crash conditions mandated by the European standard EN 1317 (European Standard 1998). Itoh et al. (2007) simulated the progressive impact of a heavy truck on a concrete barrier using *LS-DYNA* and compared the accuracy of the FEM models with full-scale on-site testing results. Liu (2011) investigated the dynamic crushing behaviors of steel box beams focusing on the effect of strain hardening and strain rate effects. Sharma et al. (2012) developed a framework for estimation of the dynamic shear force capacity of an RC column subject to vehicle impact. Tay et al. (2012) carried out a vehicular crash test of a security bollard and compared the results with those of numerical simulations using two different loading approaches in *LS-DYNA*.

In practice, protection against progressive collapse is considered by the alternate path (AP) method, which is a prescriptive approach that allows a designer to incorporate strengthening to bridge over a removed element, thus adding robustness and redundancy throughout the structure. The U.S. Department of Defense has issued guidelines for evaluating the progressive collapse potential of a structure (UFC 2013) specifying standard procedure for the AP approach. Many researchers evaluated the progressive collapse resisting capacity of structures based on the AP approach (Marjanishvili 2004; Tsai and Lin 2008; Kim et al. 2013).

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This study investigates the performance of three-story steel moment frames subjected to vehicle collision at a first-story column through numerical simulation using *LS-DYNA*. The finite-element model of a vehicle provided by the National Crash Analysis Center (NCAC) (2010) was used for numerical analysis. Before carrying out the impact analysis, the nonlinear dynamic time-history analyses were carried out first to evaluate the progressive collapse potential of the model structures based on the AP approach.

Analysis Modeling of the Vehicle and the Case Study Structures

The vehicle used in the impact analysis is the 8-t single unit truck shown in Fig. 1 provided by the NCAC, and the detailed finite-element modeling information is shown in Table 1. The vehicle is built on a main longitudinal rail structure that acts as its backbone. The rails are made of the high strength low alloy (HSLA) steel with yield stress of 350 MPa. The yield stress of the steel forming the surface of the truck is 155 MPa, and that of the other components is 270 MPa. The mass density and elastic modulus of steel used in the model are 7.85 $kN/m^2/g$ and 205,000 MPa, respectively. It was assumed that 2.8 t of mass is loaded on the truck, which leads to total mass of 8.035 t. The material data obtained from the American Iron and Steel Institute (2014) were used for material model.

Fig. 2 shows the stress-strain relationship of the A36 and A572 steel of which the beams and columns are made. The analysis model structures are three-story three-bay moment resisting frames with 5- and 10-m span length as shown in Fig. 3. The beams and columns are designed with steel H-shaped members with A36 and A572 steel, respectively. The cross-sectional information is shown in Fig. 4. The structure was designed with dead and live loads of 5 and 3 kN/m^2, respectively, and the lateral load was not considered. Two horizontal continuity plates are located between column flanges across the connections at the level of beam flanges. The limit strain or the elongation at break was assumed to be 0.2, 0.18, and 0.1 for beams, columns, and connections, respectively. Table 2 shows the material properties of the model structure. The structural elements were modeled using an eight-node hexahedron solid element, and Fig. 5 depicts the finite-element mesh of a typical

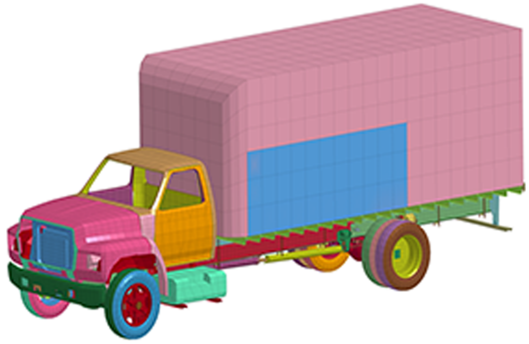

Fig. 1. Finite-element modeling of F800 truck

Table 1. FE Model Parameters of the Truck Used in the Impact Analysis

Parameters		Quantities
Number of elements	Shell	19,479
	Solid	1,248
	Beam	124
Weight of vehicle (kg)		8,035
Elastic modulus (MPa)		205,000
Impact velocity (km/h)		40, 80, 120
Vehicle geometry [B × H × L (mm)]		2,400 × 3,200 × 8,500

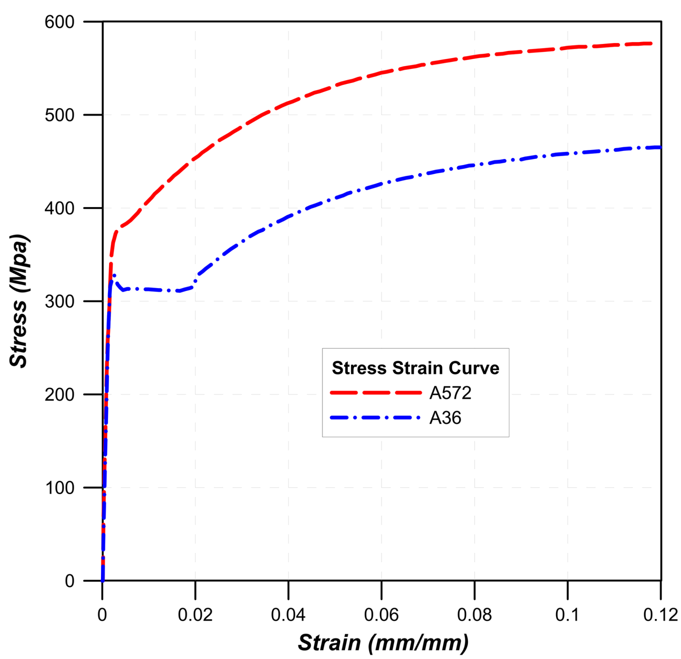

Fig. 2. Stress-strain curve of structural steel used in the analysis

beam-column joint. The first-story columns were assumed to be embedded in a rigid medium as done by Ferrer et al. (2010).

In this study, impact analysis of the model structures was conducted using the program code *LS-DYNA*, which is a general-purpose simulation software package performing nonlinear transient dynamic finite-element analysis using explicit time integration. The elements of the example structures subjected to vehicle impact were modeled using the elastoplastic material named MAT_PIECEWISE_LINEAR_PLASTICITY, and the contact condition between the structure and the vehicle was defined by the CONTACT_AUTOMATIC_SURFACE_TO_SURFACE keyword. The friction coefficient between the ground and the wheels was assumed to be 0.01, and the ground was modeled by shell elements with the MAT_RIGID keyword to prevent energy dissipation owing to deformation of the ground. In materials that undergo extremely large deformations, an element may become so distorted that the volume of the element may be calculated as negative. In this study, the CONTACT_INTERIOR keyword was used to prevent the occurrence of negative volume owing to large deformation in the vehicle.

Materials can behave differently at high-speed dynamic events such as vehicle impact. In this study, high strain-rate effect was accounted for using the Cowper-Symonds model (Cowper and Symonds 1958), which scales the yield stress by the strain rate dependent factor as follows:

$$\sigma_y = \left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/P}\right]\sigma_0$$

where ε = strain rate during dynamic crushing; and C and P = Cowper-Symonds strain rate parameters. In this study, the values of 40 and 5 were used for C and P, respectively, based on Liu (2011). In the impact analysis, the original yield strength σ_0 of all structural elements was replaced by the dynamic flow stress σ_y considering the strain-rate effects.

Evaluation of the Progressive Collapse Potential Based on the AP Approach

Progressive collapse is the effect of local damage to structural elements, which results in global collapse of the structure. From a series of accidents, to prevent progressive collapse, a structure should have sufficient continuity to offer an alternative path to stability of the structure even if a vertical load-resisting element is removed. To prevent progressive collapse, the U.S. Department of Defense presented a guideline for buildings (UFC 2013). The alternate path (AP) approach recommended in the UFC guidelines is a prescriptive approach that allows a designer to incorporate structural strengthening to bridge over a removed element, thus adding robustness and redundancy throughout the structure.

Progressive collapse is generally initiated by the sudden loss of one, or many, structural members. Once a structural member (usually a column in the first story) is suddenly removed, the stiffness matrix of the system also needs to be suddenly changed. This may cause difficulty in the analytical modeling process. To avoid this problem, all member forces are first obtained from the full structural model subjected to the applied load. The structure is then remodeled with the appropriate column removed, and its member forces are applied to the structure as ramp forces to maintain equilibrium as shown in Fig. 6. After the vibration caused by the applied gravity load and the reaction forces disappear, the member force is suddenly removed to initiate progressive collapse. In this way, the progressive collapse analysis starts from the moment that the structure is already deformed by the gravity load, which reflects the actual loading situation quite realistically.

In this study, the arbitrary sudden column removal analysis of the model structure was conducted using the nonlinear analysis program package *PERFORM-3D* to evaluate the progressive collapse potential of the model structures based on the alternate path approach recommended in UFC (2013). The performance criteria provided in the ASCE/SEI 41-06 (ASCE 2007) were used to define damage states of the model structures, which are the immediate occupancy (IO), life safety (LS), and the collapse prevention (CP) states. Such criteria are also recommended in the UFC guidelines (UFC 2013) for progressive collapse.

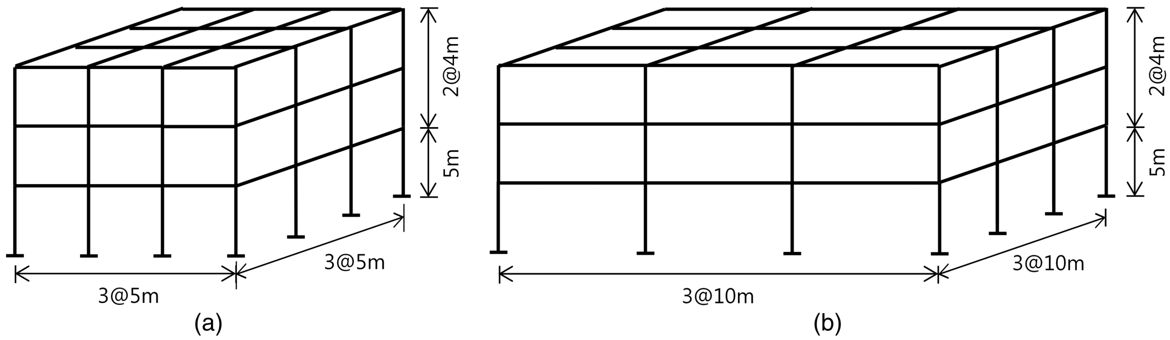

Fig. 3. Configurations of analysis model structures: (a) 5-m span model; (b) 10-m span model

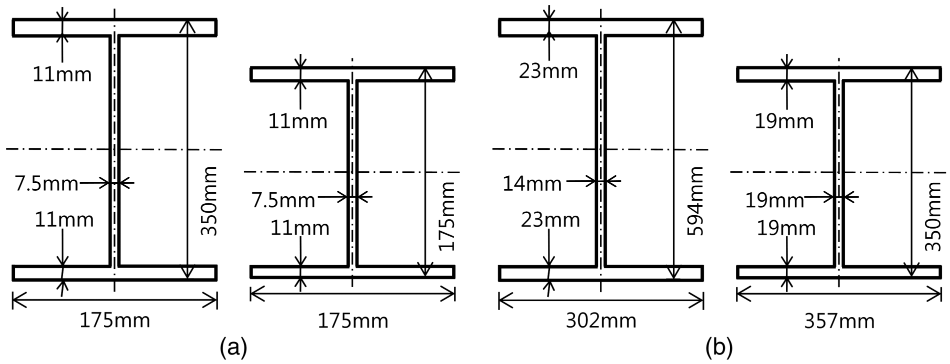

Fig. 4. Cross-sectional dimensions of the beams and columns of model structures: (a) 5-m span model; (b) 10-m span model

Table 2. Structural Properties of the Analysis Models

Properties		Quantities
Yield stress (MPa)	Beam	250
	Column	345
Elongation at break	Beam	0.2
	Column	0.18
	Weld	0.1
Elastic modulus (MPa)		205,000
Poisson's ratio		0.3

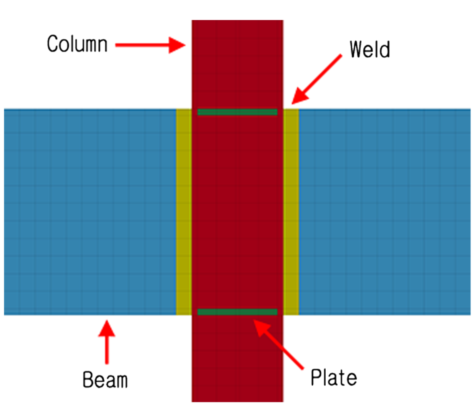

Fig. 5. FE mesh generation of a beam-column connection

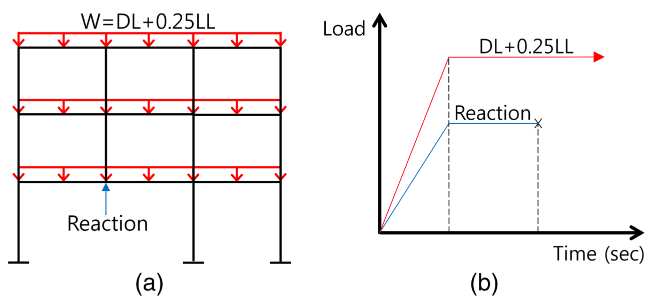

Fig. 6. Application of dynamic load case for sudden column removal analysis for progressive collapse: (a) applied loads and column reaction force; (b) time history of applied load and column reaction force

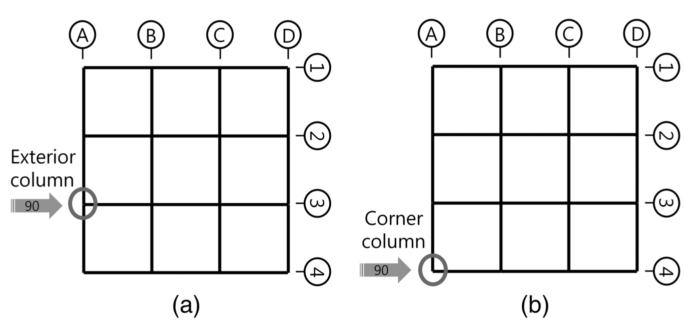

Fig. 7. Location of the removed columns: (a) exterior column (A3); (b) corner column (A4)

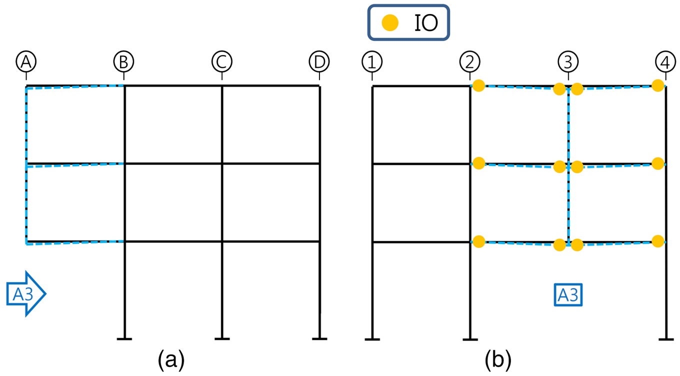

Fig. 8. Damaged configuration of the 5-m span model structure subjected to sudden loss of exterior column: (a) side view; (b) front view

Fig. 7 shows the location and the naming of the removed exterior and corner columns for application of the AP method. Fig. 8 shows the damaged configuration of the 5-m span model structure subjected to sudden loss of the exterior column, where the damages in the elements are in the IO state, and the progressive collapse did not occur. Fig. 9 shows the vertical displacement time history at the beam-removed column joint, which indicates stable behavior.

The damage caused by the sudden removal of both the exterior and the adjacent interior columns is presented in Fig. 10, where the plastic hinges formed are in the IO stage, and no plastic hinges are found in the first-story columns. Fig. 11 shows that the time history of the vertical displacement of the arbitrary removal of the two columns resulted in stable oscillation around the vertical displacement of 75 mm.

Fig. 12 depicts the damaged configuration and the plastic hinge formation of the 5-m span model structure subjected to sudden

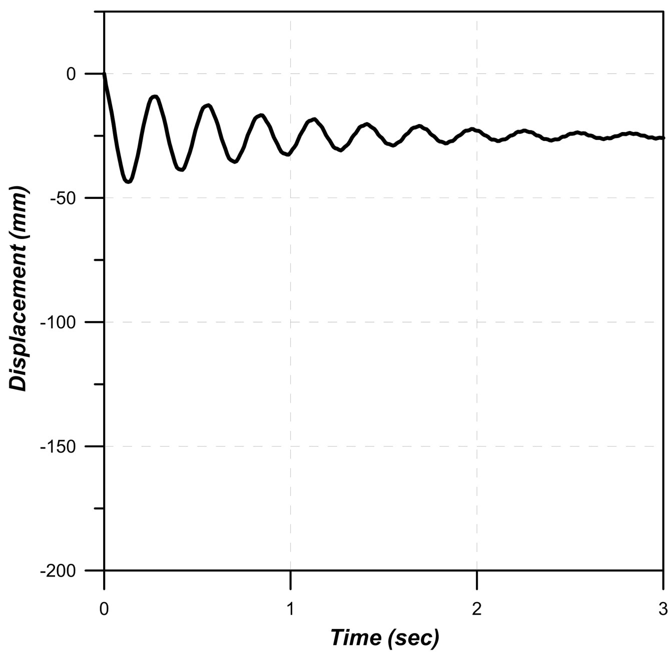

Fig. 9. Vertical displacement of the 5-m span model structure subjected to sudden loss of the exterior column

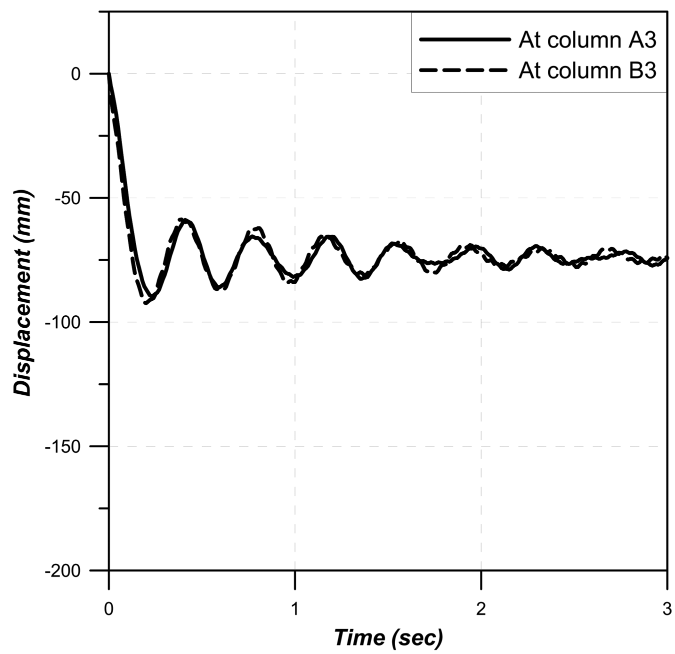

Fig. 11. Vertical displacement of the 5-m span structure subjected to sudden loss of an exterior and adjacent interior column

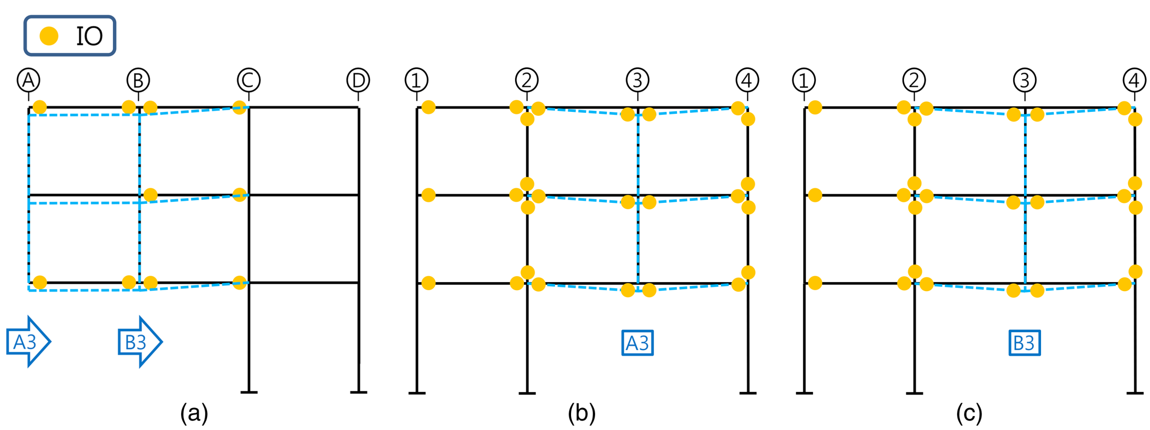

Fig. 10. Damaged configuration of the 5-m span structure subjected to sudden loss of exterior and adjacent interior columns: (a) side view; (b) front view (first row); (c) front view (second row)

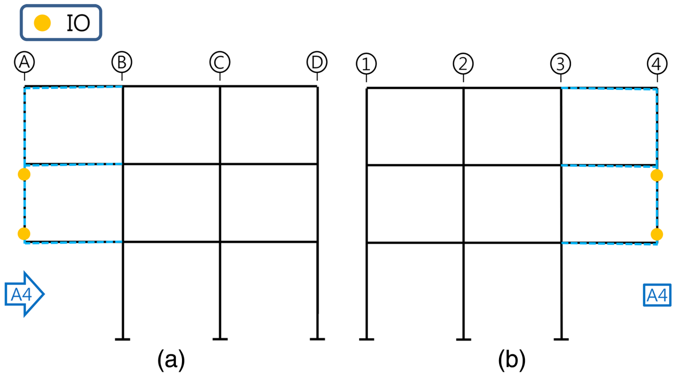

Fig. 12. Damaged configuration of the 5-m span model structure subjected to sudden loss of corner columns: (a) side view; (b) front view

removal of the first-story corner column, where plastic hinges formed in the second-story column right above the removed column. Fig. 13 depicts the vertical displacements of the model structure, which shows that the model structure remained stable after the column removal.

The simultaneous removal of both the corner column and the adjacent exterior column resulted in the IO state damage in the members above the removed columns as shown in Fig. 14. The vertical displacements at the joints of the A4 and B4 columns plotted in Fig. 15 show that the structure remained stable after sudden removal of the two columns at the same time.

Fig. 16 shows the damaged configuration and the plastic hinge formation of the 10-m span structure subjected to sudden removal of an exterior column, and the vertical displacement time history is shown in Fig. 17. The plastic hinges formed in all beams right above the damaged column, the plastic hinge rotations belong to the IO state, and slight damage occurred in the nearby columns.

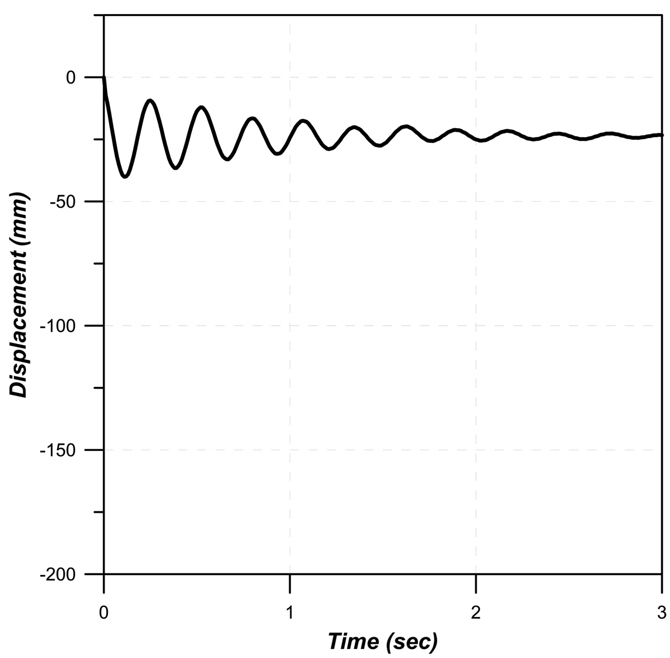

Fig. 13. Vertical displacement of the 5-m span model structure subjected to sudden loss of a corner column

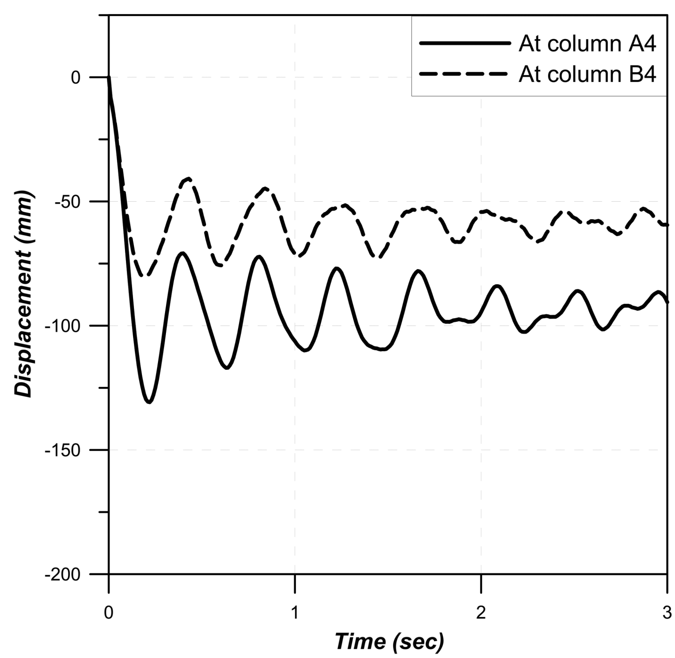

Fig. 15. Vertical displacement of the 5-m span structure subjected sudden loss of a corner and adjacent exterior columns ($v = 80$ km/h)

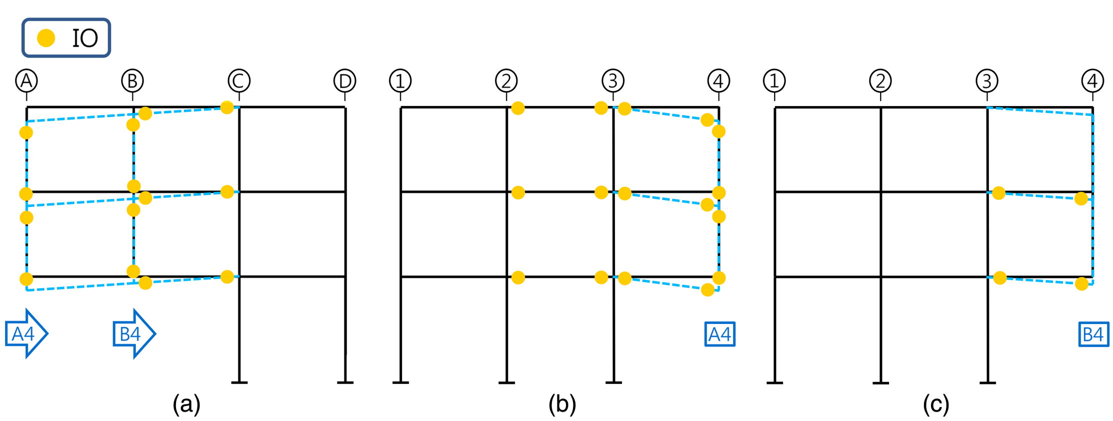

Fig. 14. Damaged configuration of the 5-m span structure subjected to sudden loss of corner and adjacent exterior columns: (a) side view; (b) front view (first row); (c) front view (second row)

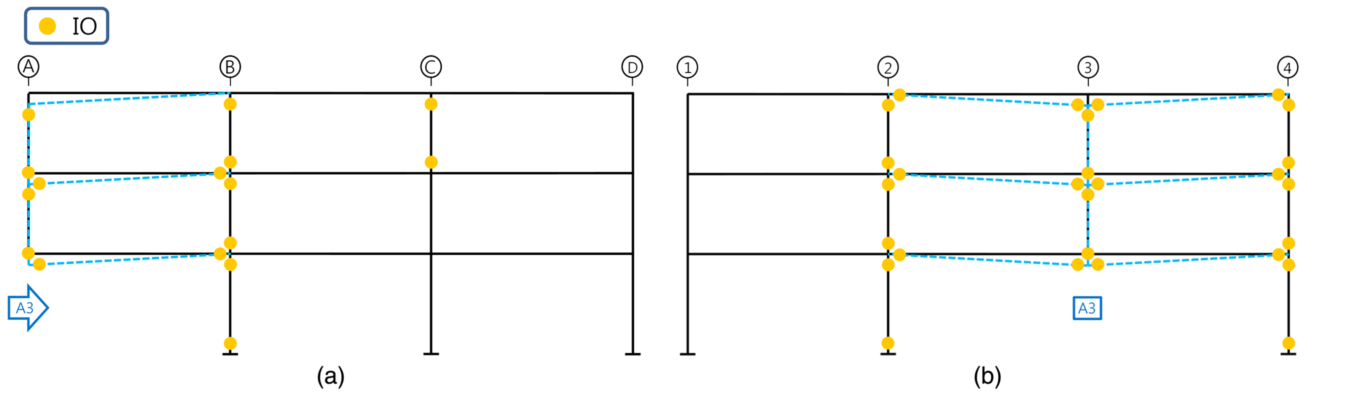

Fig. 16. Damaged configuration of the 10-m span model structure subjected to sudden loss of an exterior column: (a) side view; (b) front view

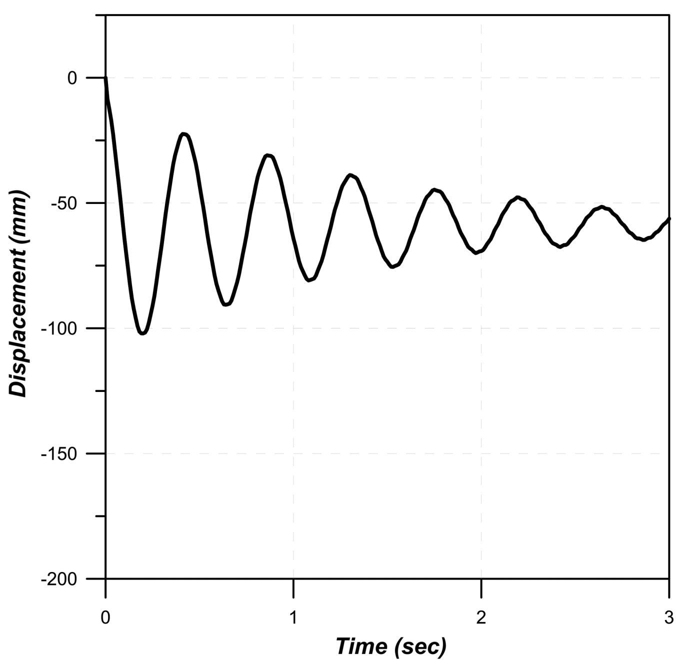

Fig. 17. Vertical displacement of the 10-m span model structure subjected to sudden loss of an exterior column

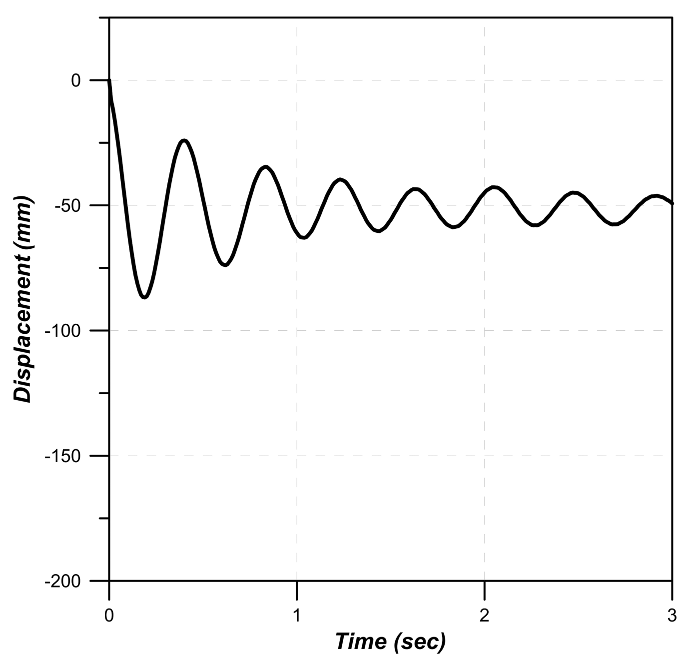

Fig. 19. Vertical displacement of the 10-m span structure subjected to sudden loss of a corner column

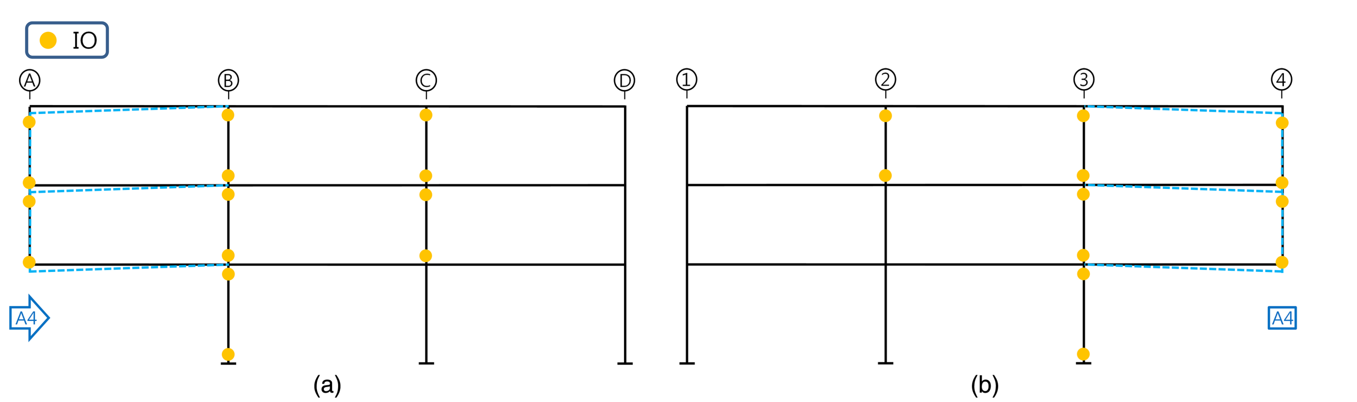

Fig. 18. Damaged configuration of the 10-m span structure subjected to sudden removal of a corner column: (a) side view; (b) front view

The displacement time histories show that the structure remained stable after arbitrary sudden removal of the exterior column. The vertical displacement in the 10-m span structure subjected to the arbitrary removal of the exterior column turned out to be more than twice as large as that of the 5-m span structure as shown in Figs. 9 and 17.

Fig. 18 shows the damaged configuration and the plastic hinge locations of the 10-m span structure subjected to sudden removal of the corner column. Only minute damage in the IO state of plastic deformation occurred in the structure; however, plastic hinges were also observed in the third-story columns in the adjacent exterior spans. Fig. 19 depicts the vertical displacement of the 10-m span structure subjected to sudden loss of a corner column obtained from nonlinear dynamic analysis. It can be observed that the structure remained stable after the sudden removal of the corner column.

The nonlinear dynamic analysis results presented in this section confirmed that the model structures had enough strength and redundancy to bridge over the lost critical element to prevent progressive collapse in terms of the alternate path approach of the UFC guidelines (UFC 2013).

Table 3. Failure Criteria for Structural Steel Elements Subjected to Extreme Loads (Reprinted from ASCE 1999, © ASCE)

Element	Material properties	Failure type	Criteria	Damage: Light (%)	Damage: Moderate (%)	Damage: Severe (%)
Beam	Steel	Bending/ membraneresponse	δ/L	5	12	25
		Shear	γ_v	2	4	8
Column		Compression	$\Delta L/L$	2	4	8

Note: δ/L = ratio of center line deflection to span; γ_v = average shear strain across section; $\Delta L/L$ = ratio of shortening to height.

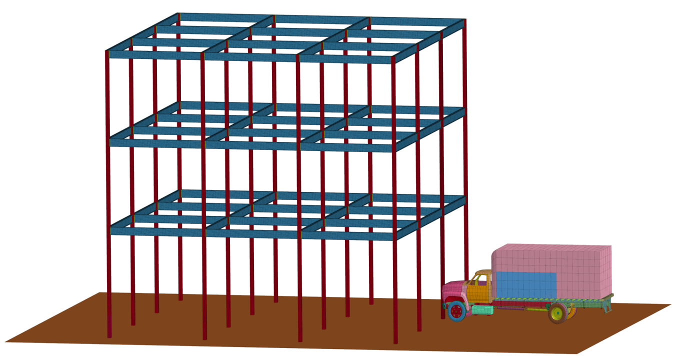

Fig. 20. 3D view of the truck collision with the model structure

Vehicle Impact Analysis Results of the Model Structures

In this section, the analysis results of the model structures obtained from the vehicle collision were presented. For identification of the damage state, the four-level performance criteria for extreme loads specified in ASCE (1999) were used, which are the light, moderate, severe, and failure states as shown in Table 3. Fig. 20 shows the 3D view of the collision of the vehicle to the first-story exterior column of the analysis model. The locations of the collided columns and the direction of impact are shown in Fig. 7.

Fig. 21 shows the damaged configuration of the 5-m span model structure subjected to the vehicle impact with speed of 40 km/h. As a result of the collision, the bottom end of the first-story exterior column was separated from the support. After the first collision, the vehicle went through the exterior column and hit the interior column to bend it slightly. The damages in other elements are within the light to moderate state. No progressive collapse was observed as a result of the vehicle impact. This can be confirmed in Fig. 22, which shows the vertical displacement at the beam-removed column joint. Although the results indicate stable behavior, the vertical displacement obtained from the impact analysis turned out to be much larger than the displacement obtained from the AP method shown in Fig. 9. This seems to be reasonable based on the observation that more members are damaged as a result of vehicle collision, which is observed in Figs. 8 and 21.

Fig. 23 depicts the damaged configuration of the 5-m span model structure subjected to vehicle impact on the corner column with speed of 40 km/h. The plastic hinge formation and the deformed shape are similar to those of the vehicle impact on the exterior column with the same speed. Fig. 24 shows the vertical displacements of the 5-m span model structure subjected to vehicle impact on a corner column, where the displacement is more than twice the displacement obtained from the impact on the exterior column. In this case no progressive collapse was observed in the model structure.

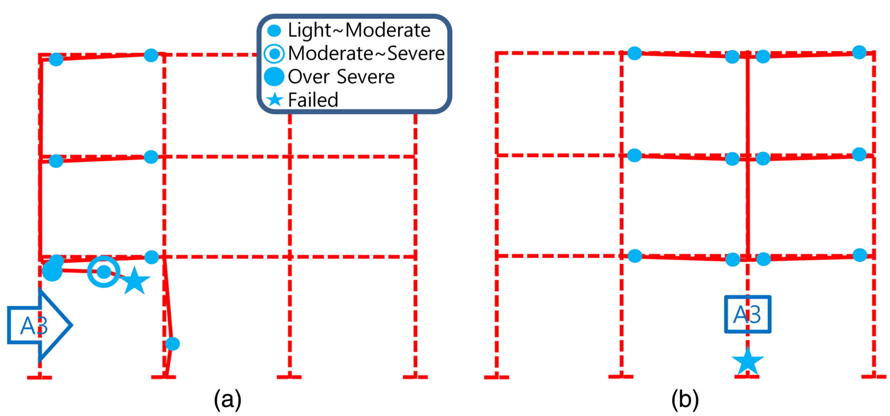

Fig. 21. Damaged configuration of the 5-m span model structure subjected to car impact on an exterior column ($v = 40$ km/h): (a) side view; (b) front view

Fig. 25 shows the damaged configuration of the 5-m span structure subjected to vehicle impact with the speed of 80 km/h. Both the exterior and the adjacent interior columns were separated from the bottom joints as a result of the collision. The remaining columns in the impacted frame were damaged between the moderate to severe states. After collision of the vehicle with the structure, the vertical displacements of the joints of the columns A3 and B3 increased until collapse as shown in Fig. 26. This is different from the result of the arbitrary sudden removal of the two columns shown in Fig. 11, which resulted in stable oscillation around the vertical displacement of 75 mm. Also in the configuration of the damaged structure shown in Fig. 24, significant lateral displacement occurred along the impact direction, which implies that significant lateral load was applied during the vehicle impact. The application of the large lateral load as well as the vertical movement of the structure caused by sudden loss of the column resulted in quite different responses of the model structure from those obtained from the AP approach, which involves only the vertical vibration generated by sudden column removal.

The deformed configuration and the plastic hinge formation attributable to impact of the vehicle on the corner column of the 5-m span structure with speed of 80 km/h are depicted in Fig. 27, in which both the impacted corner column and the adjacent exterior column were severed from the joints, and the remaining two columns in the line were severely damaged. As a result of the collision, significant side sway occurred, and the structure almost collapsed. The vertical displacements at the joints of A4 and B4 columns plotted in Fig. 28 show that right after the vehicle impact, the vertical displacements increased rapidly without oscillation.

Fig. 29 shows the damaged configuration of the 10-m span model structure subjected to vehicle impact on an exterior column with speed of 120 km/h, and the vertical displacement time history is shown in Fig. 30. The analysis results of the impact with speeds of 40 and 80 km/h were not presented because the damage in

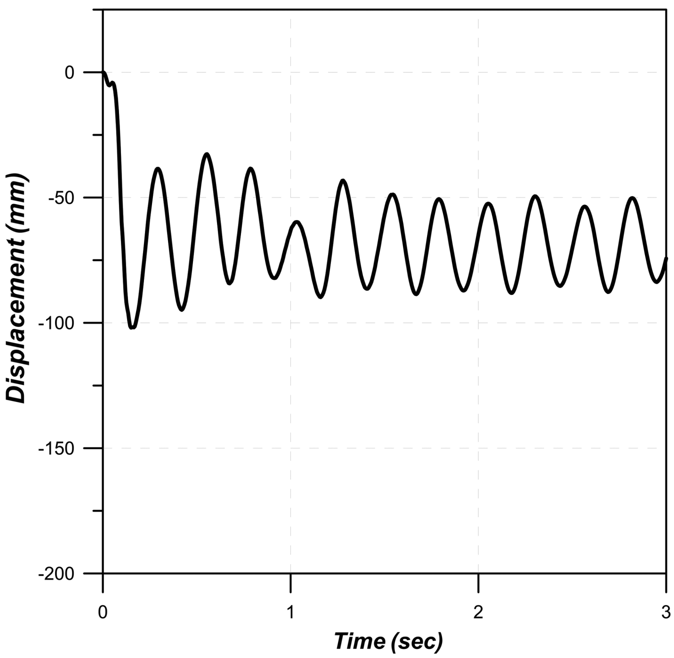

Fig. 22. Vertical displacement of the 5-m span model structure subjected to car impact of the exterior column with $v = 40$ km/h

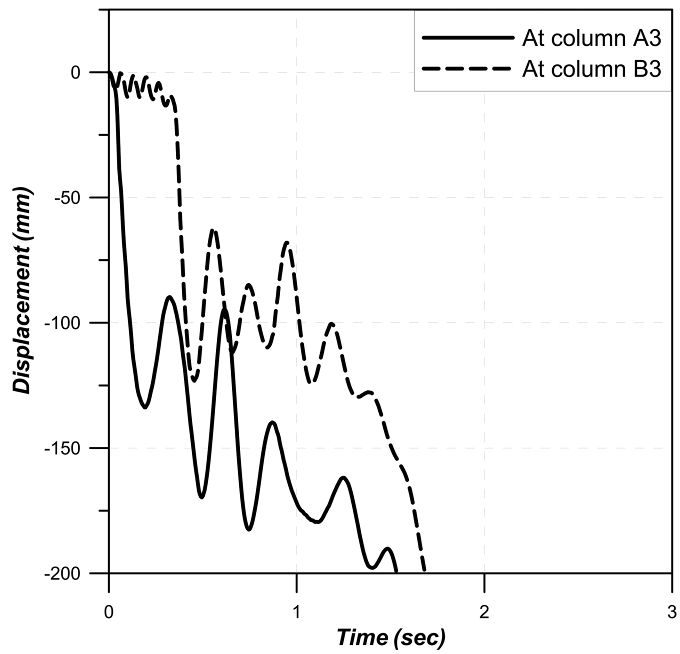

Fig. 24. Vertical displacement of the 5-m span model structure subjected to car impact of the corner column ($v = 40$ km/h)

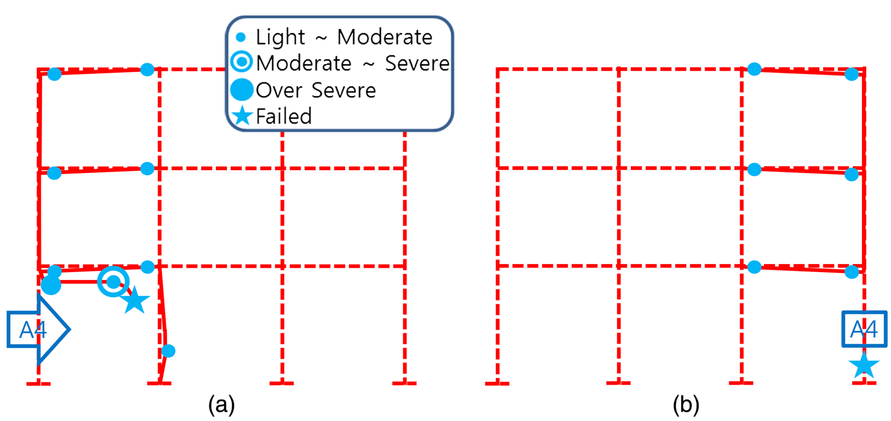

Fig. 23. Damaged configuration of the 5-m span model structure subjected to car impact on a corner column ($v = 40$ km/h): (a) side view; (b) front view

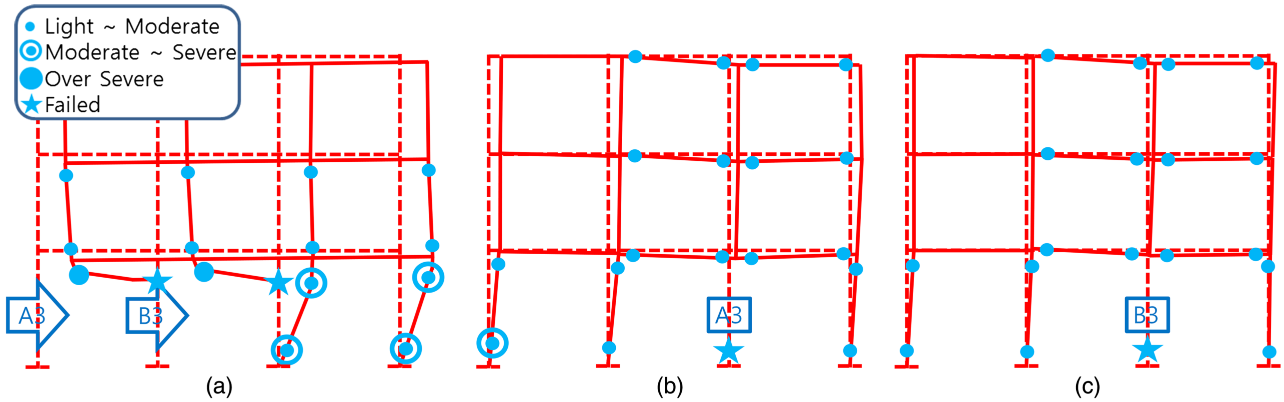

Fig. 25. Damaged configuration of the 5-m span structure subjected to car impact ($v = 80$ km/h): (a) side view; (b) front view (first row); (c) front view (second row)

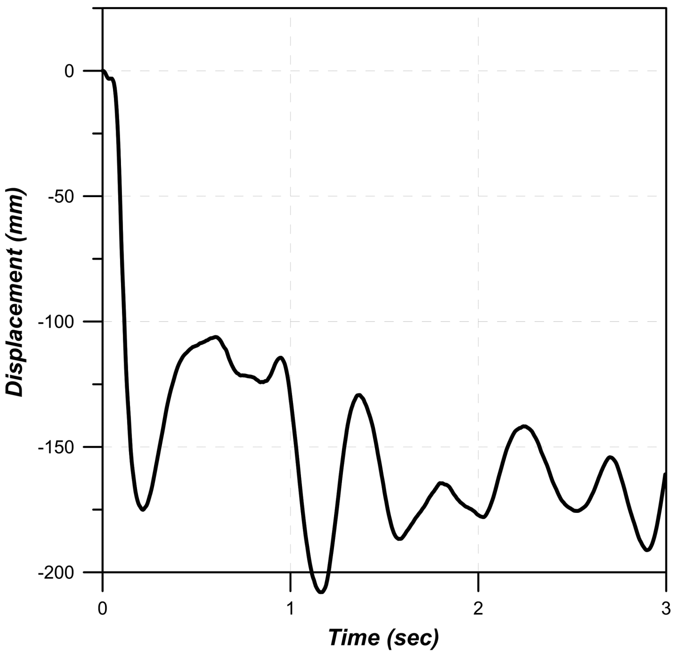

Fig. 26. Vertical displacement of the 5-m span structure subjected to car impact of an exterior and adjacent interior column ($v = 80$ km/h)

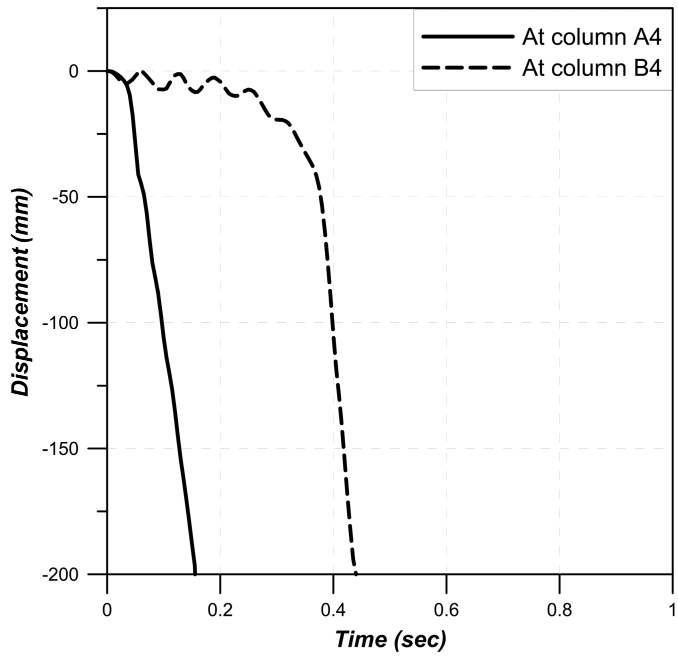

Fig. 28. Vertical displacement of the 5-m span structure subjected to car impact on a corner and adjacent exterior column ($v = 80$ km/h)

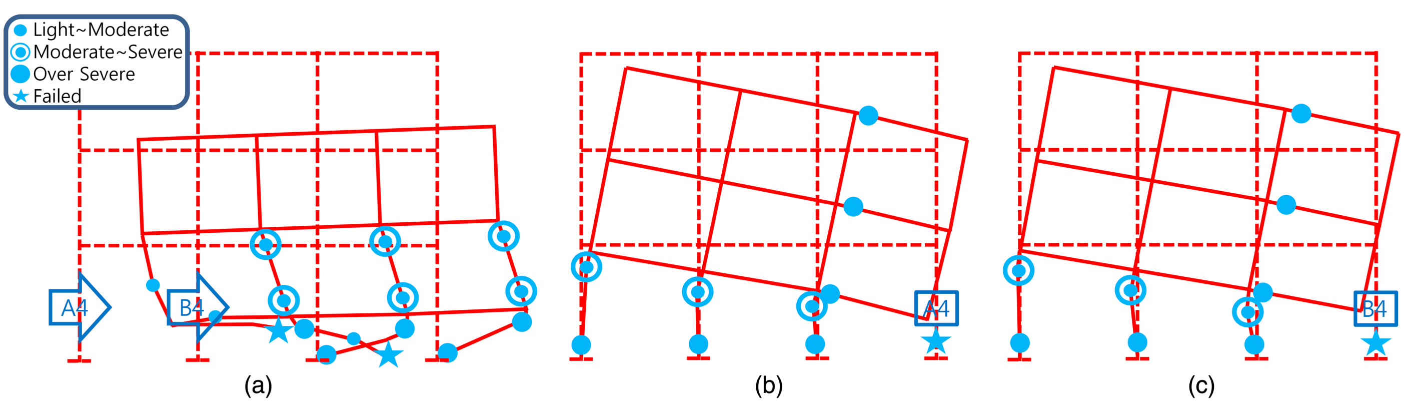

Fig. 27. Damaged configuration of the 5-m span structure subjected to car impact on corner and adjacent exterior columns ($v = 80$ km/h): (a) side view; (b) front view (first row); (c) front view (second row)

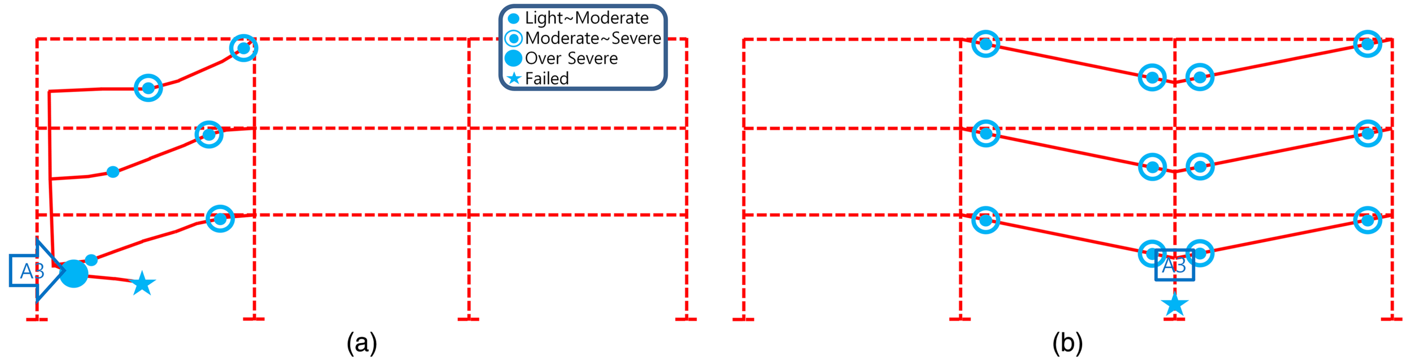

Fig. 29. Damaged configuration of the 10-m span model structure subjected to car impact on an exterior column ($v = 120$ km/h): (a) side view; (b) front view

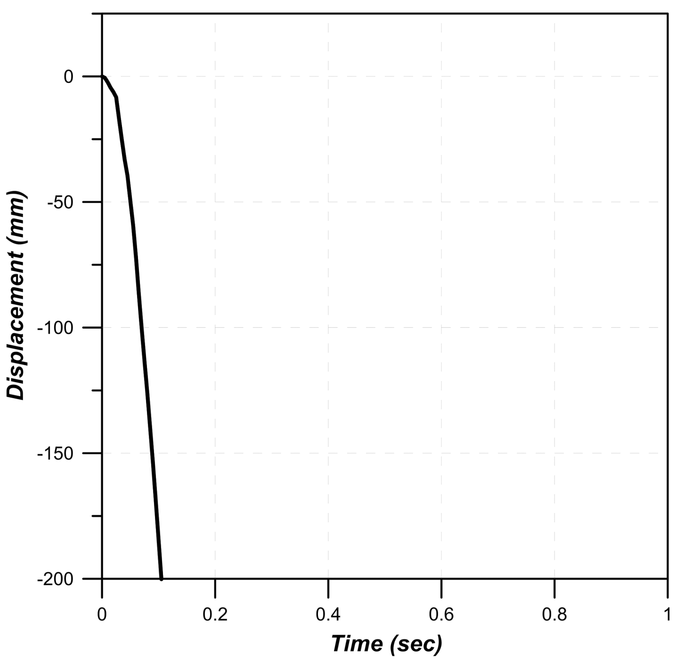

Fig. 30. Vertical displacement of the 10-m span model structure subjected to car impact on an exterior column ($v = 120$ km/h)

the impacted column was not so severe. The figure shows that although the column size was increased compared with the size of the structure with 5-m span length, the column was completely separated from the joint, and plastic hinges formed in all beams right above the damaged column after the impact. The displacement time histories show that progressive collapse occurred as a result of the vehicle impact. This is different from the result of the AP method in which the structure remained stable after sudden removal of the exterior column.

Fig. 31 shows the damaged configuration and the plastic hinge locations of the 10-m span structure subjected to vehicle impact at the corner column with $v = 120$. The columns and beams directly above the lost column are severely damaged from the vehicle impact. The roof beam in the corner span as well as the impacted column completely failed as a result of the impact. However, the damage was not expanded to the adjacent spans. As in the previous case, vertical displacement increased rapidly without oscillation, and progressive collapse occurred right after the collision.

Conclusions

This study investigated the performance of three-story steel moment frames subjected to vehicle collision at a first-story column through finite-element analysis. The nonlinear dynamic time-history analyses specified in the alternate path approach of the

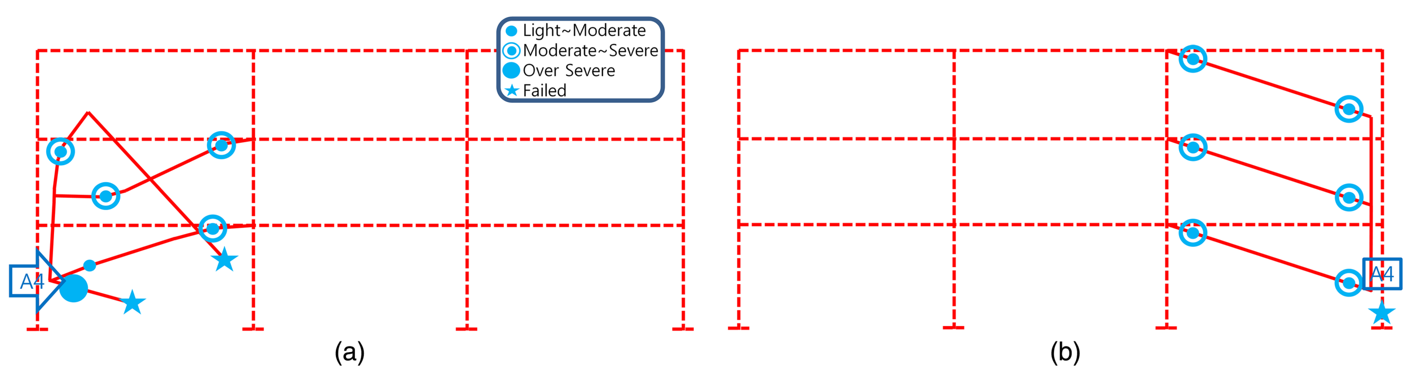

Fig. 31. Damaged configuration of the 10-m span structure subjected to car impact at a corner column with $v = 120$ km/h: (a) side view; (b) front view

UFC guidelines (UFC 2013) showed that the model structures had enough strength and redundancy to bridge over the lost critical element to prevent progressive collapse. The impact analysis showed that the model structures remained stable when the vehicle collided with a first-story column at the speed of 40 km/h. However, at the speeds of 80 and 120 km/h, the model structures were severely damaged by the impact and followed progressive collapse after the vehicle passed through the exterior or the corner column and collided with the adjacent column in its path. The damage caused by the collision to the corner column was far greater than the damage attributable to collision to the exterior column.

The analysis results showed that although the analysis model structures satisfied the UFC guidelines (UFC 2013) for progressive collapse in terms of the alternate path approach, they were severely damaged owing to progressive collapse when subjected to impact of a vehicle with significantly high speed. Therefore, for a structure exposed to possible impact of a high-speed vehicle, to provide an alternate load path for a lost column to ensure robustness and redundancy may not be enough to ensure against progressive collapse. In this case, to prevent direct access of vehicles to columns using protective structures such as security bollards may be required in addition to providing an alternate load path.

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