Analysis of Steel Moment Frames subjected to Vehicle Impact

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Abstract

Structures are often subject to vehicle collision which can be accidental or intentional as in the case of a terrorist attack. This study investigates the performance of a 2D and a 3D steel moment frame subjected to vehicle collision at a first story column using LS-DYNA. The finite element models of vehicles provided by the National Crash Analysis Center (NCAC) are used for numerical analysis. Nonlinear dynamic time history analysis of the 2D model structure is carried out based on the arbitrary column removal scenario and the vertical displacement of the damaged structure is compared with that obtained from collision analysis. The analysis results show that the model structure remain stable when the speed of the car is 40km/h. However at the speed of 80 and 120 km/h both the 2D and 3D structures collapse by progressive collapse. The vertical displacement of the damaged joint obtained from collision analysis is significantly larger than the displacement computed based on the arbitrary column removal scenario.

Keywords: Vehicle Collision, Progressive Collapse, FEM Explicit Analysis, LS-DYNA[®].

1. Introduction

Recently the collision of vehicles with structures has increased due either to accidents or to terrorist attack. It has been reported that 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. 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 vehicular crash test of a security bollard, and compared the results with those of numerical simulations using two different loading approaches in LS-DYNA.

The damage caused by vehicle collision may result in progressive collapse in structures. U.S. Department of Defense has issued guidelines for evaluating the progressive collapse potential (UFC, 2013). Many researchers such as Kim and Choi (2013) evaluated the progressive collapse resisting capacity of structures based on the arbitrary column removal scenario specified in the UFC guidelines.

This study investigates the performance of steel moment frames subjected to vehicle collision at a first story column through numerical simulation using LS-DYNA®. The finite element models of vehicles provided by the National Crash Analysis Center (NCAC) are used for numerical analysis. Nonlinear dynamic time history analyses are carried out with three bay 2D and 3D steel structures subjected to a car impact in a first story column. The vertical displacements of the damaged structure obtained from the collision and the arbitrary column removal method recommended in the UFC guidelines are compared.

2. Analysis modeling

Materials can behave very differently at the higher strain rates typical of moderate to high-speed dynamic events such as impact. In this study high strain rate effect is accounted for using the Cowper-Symonds model which scales the yield stress by the strain rate dependent factor as follows:

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

(1)

where, $\dot{\varepsilon}$ is the strain rate during dynamic crushing, *C* and *p* are the Cowper-Symonds strain rate parameters. In the impact analysis the original yield strength σ_0 is replaced by the dynamic flow stress σ_y considering the strain rate effects.

The automobile used in the impact analysis is the eight-ton single unit truck shown in Fig. 1 provided by the NCAC (National Crash Analysis Center), 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 material of the rails is specified in the Service Manual as the High Strength Low Alloy (HSLA) steel of yield point 350 MPa. The yield stress of the steel forming the surface of the truck is 155MPa, 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 205,000MPa, respectively. It was assumed that 2.8ton of mass is loaded on the truck, which leads to total mass of 8.035 ton. The material data available from the Auto/Steel Partnership [4] and American Iron and Steel Institute [5] was used to enhance the existing material model.
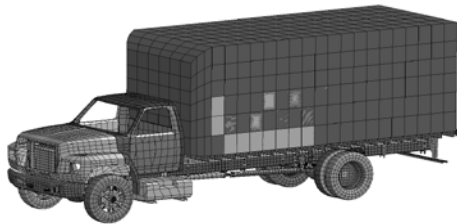
Figure 1. F800 FEM truck model

Table **1. Information of truck FEM model**

Number of element	Shell	19,479
	Solid	1,248
	Beam	124
Weight of vehicle [kg]		8035
Elastic modulus [MPa]		205,000
Impact velocity [km/h]		40, 80, 120
Vehicle geometry [B x H x L, mm]		2,400 x 3,200 x 8,500

3. Analysis of single steel column

Impact analysis is carried out on a single steel column with fixed boundary conditions at both ends. The analysis results of columns with a hollow circular (C-column), a square (S-column), and a H section shown in Fig. 2 are compared. The columns have the same length and are designed for the same loading condition. The steel columns are modeled with solid elements, and the contact condition between the column and the automobile is defined by *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE function in LS-Dyna. The friction coefficient between the ground and the wheels is assumed to be 0.01. The *CONTACT_INTERIOR condition is used to prevent the occurrence of negative volume due to large deformation of the automobile. Fig. 3 shows the stress-strain relationship of the A572 steel of which the columns are made.
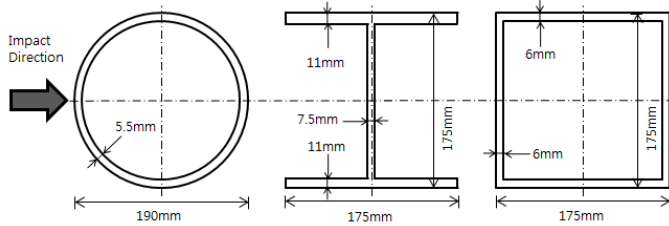
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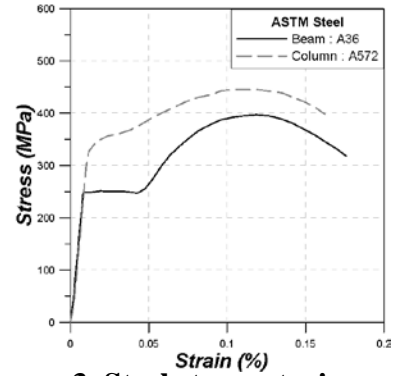**Figure 2. Cross-section of steel column**

Figure 3. Steel stress-strain curve

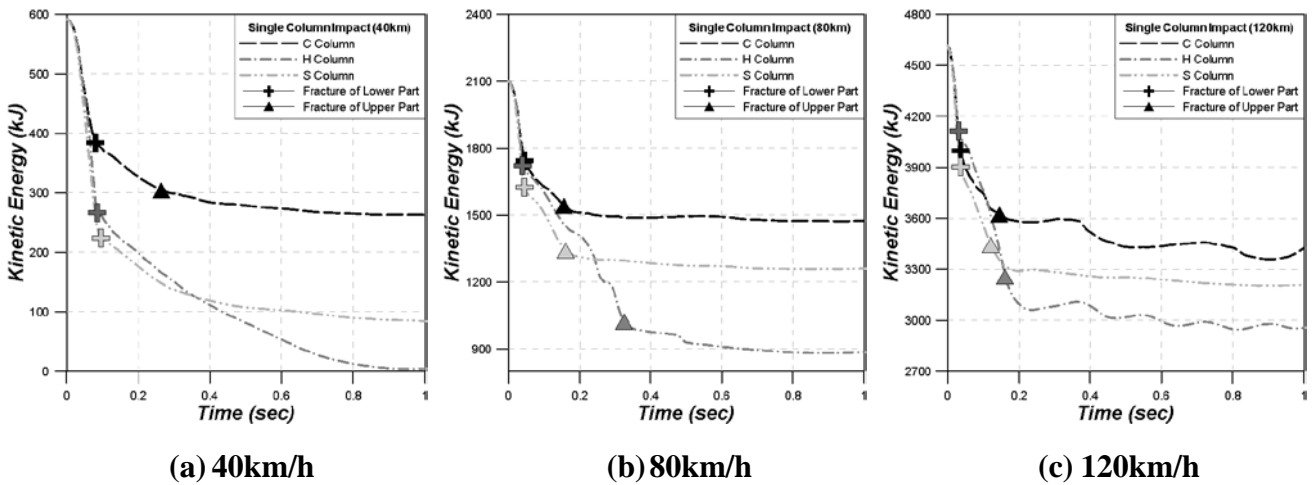(a) 40km/h (b) 80km/h (c) 120km/h

Figure 4. Variation of kinetic energy

The impact simulation is carried out with three different car speeds: 40, 80, and 120 km/h. Fig. 4 depicts the variation of kinetic energy generated during the collision. The analysis results show that in every case the rate of decrease in kinetic energy (i.e. the rate of decrease in car speed after impact) is smallest in the circular colum. The kinetic energy decreases most rapidly in the H-shaped column which has the largest cross sectional area. When the speed is 40km/h the kinetic energy associated with the collision to the H-shaped column becomes zero at 1.0 second after the impact, which implies that the car stopped completely due to the collision. On the other hand the existence of kinetic energy at 1.0 second in other columns implies that the columns are completely destroyed by the car crash and the car is still moving.
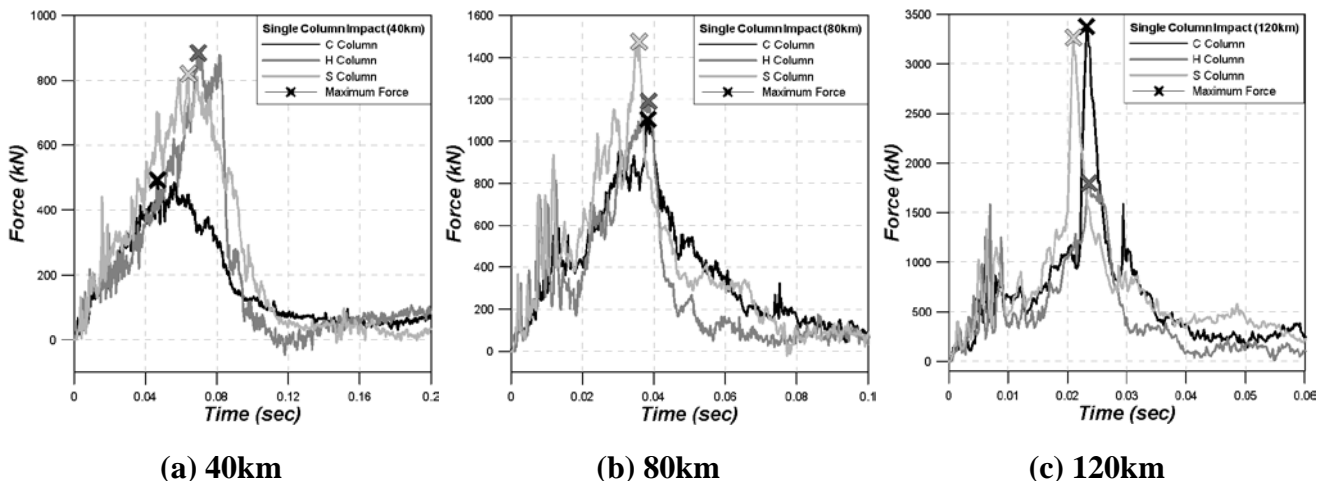

(a) 40km (b) 80km (c) 120km

Figure 5. Variation of impact force for different car speeds

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Figure 5 shows the variation of impact force for three different car speeds and the maximum values are summarized in Table 2. The impact force is smallest in the circular column when the car speed is lowest. However in the highest speed the impact force of the circular column turns out to be highest. The opposite is observed in the H-shaped column.

Table 2. Maximum force generated during the collision

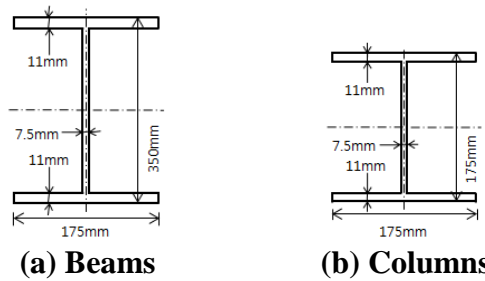| Velocity [km/h]	FEM analysis result [kN]		
	Circular column	H column	Square column
40	493.14	883.68	820.05
80	1105.60	1189.98	1475.38
120	3377.45	1798.69	3263.19
Rate of increase	680.9%	203.5%	397.9%

4. Analysis of a moment frame structure subjected to car impact

4.1 Model structure

The analysis model structure is a three-story three-bay moment resisting frame with 5m span length and 4m story height as shown in Fig. 6. 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. 7. The structure is designed with dead and live loads of 5 and 3 kN/m^2, respectively. The structure is modeled in the LS_Dyna with 416,224 solid elements. The columns are modeled to be continuous throughout the stories and the beams are welded to columns. 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 is assumed to be 0.2, 0.18, and 0.1 for beams, columns, and connections, respectively, in the analysis. Table 3 shows the material properties of the model structure, and the stress-strain curves for beams and columns are depicted in Fig. 3. Fig. 8 depicts the finite element mesh of a typical beam-column joint.
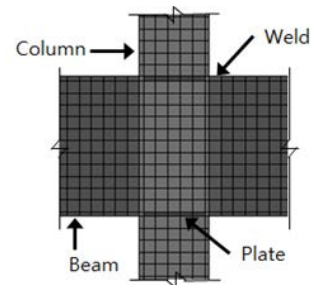

(a) Beams   (b) Columns
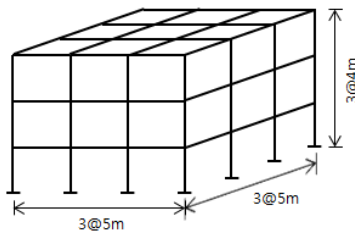
Figure 6. 3D model structure   **Figure 7. Cross-section of elements**

Table 3. Modeling information of frame

| Yield Stress	Beams	250 (MPa)
	Columns	345 (MPa)
Elongation at break	Beams	0.2
	Columns	0.18
	Weld	0.1
Elastic modulus		205,000 (MPa)
Poisson's ratio		0.3

Figure 8. FE mesh generation of a connection

4.2 Analysis results of 2D frame structure

Collision analysis is carried out with one of the internal frame separated from the 3D model structure shown in Fig. 6. Fig. 9 shows the deformed shapes of the structure 1.0 second after

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collision. It is observed that when the speed of the truck is 40km/h only the exterior column is severely damaged due to the collision with the truck but is not separated from the joint. When the car speed is increased to 80km/h the bottom of the collided column is completely separated from the joint and the left-hand-side bay collapses due to progressive collapse. At the speed of 120km/h the truck goes through the exterior column and collides with the adjacent interior column. The other first story columns are also severely damaged due to large lateral displacement.
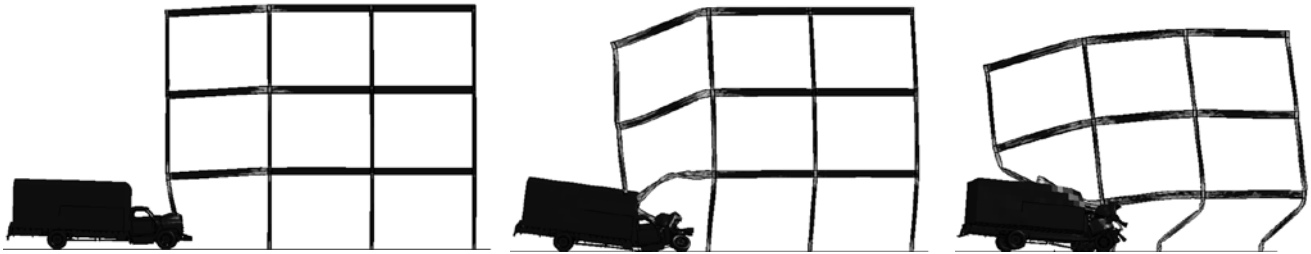

(a) 40km/h　　　　　　　(b) 80km/h　　　　　　　(c) 120km/h
Figure 9. 2D frame impact simulation results (t=1 sec.)
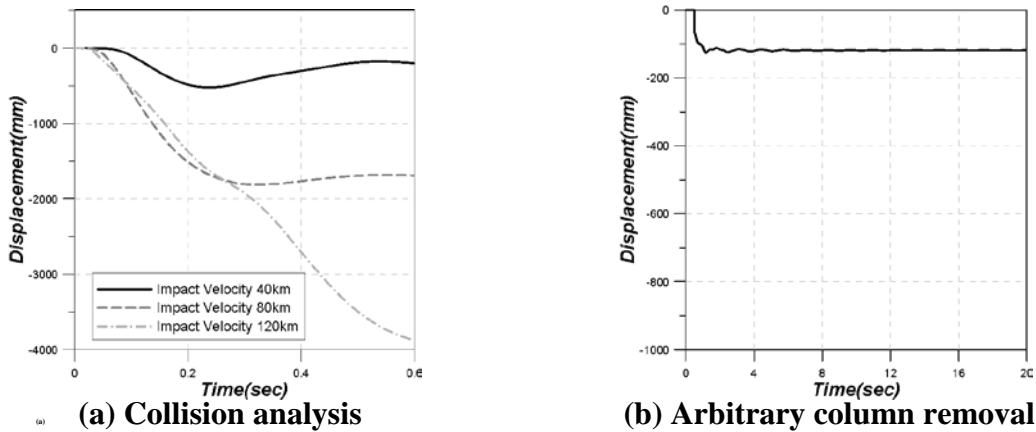
(a) **Collision analysis**　　　　　　　(b) **Arbitrary column removal**
**Figure 10. Vertical displacement obtained from collision analysis and
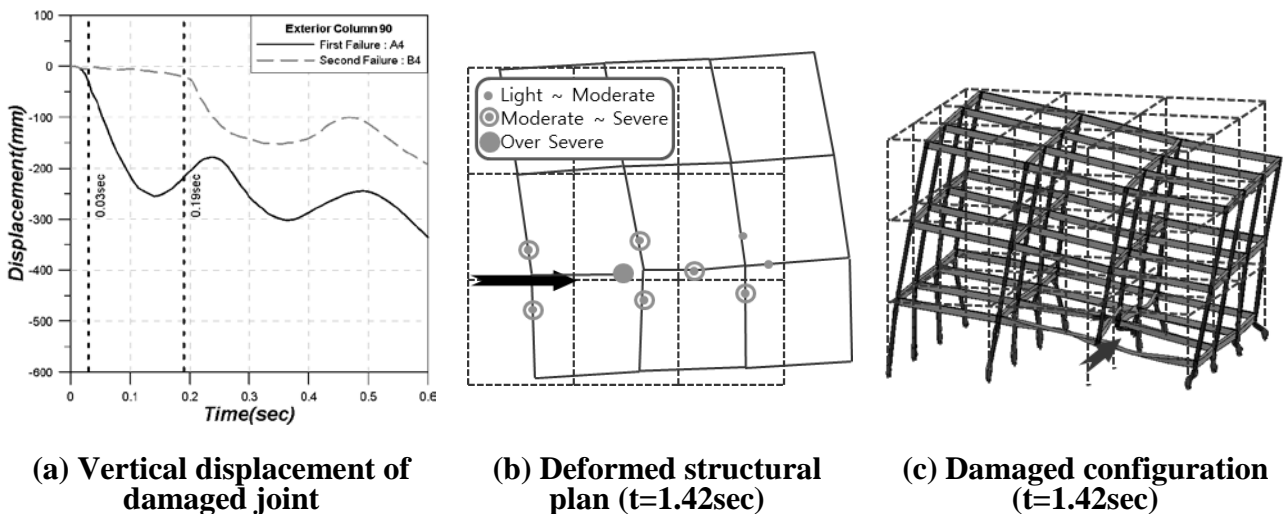arbitrary column removal method**

Figure 10(a) shows the vertical displacement of the first story exterior beam-column joint obtained from the collision analysis with three different car speed. It can be observed that at the speeds of 40 and 80km/h the collision results in significant vertical displacements but the vertical displacements remain stable. However at the speed of 120km/h the vertical displacement decreases almost unbounded, which implies collapse of the structure. Fig. 10(b) depicts the vertical displacement at the same point obtained by arbitrary sudden removal of the first story column. Compared with the results of the collision analysis, the vertical displacement obtained by the arbitrary removal of the column is significantly smaller. This is due to the fact that after collision the catenary force caused by the large bending deformation of the column pulls the joint down, which cannot be considered in the arbitrary column removal scenario.

4.3 Analysis result of 3D framed structure

| a) Frame impact simulation | (b) Exterior column | (c) Corner column |
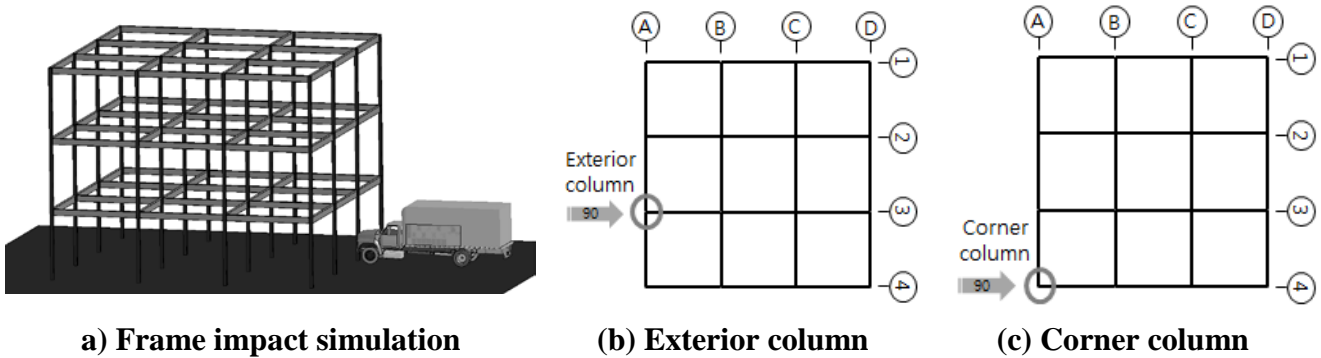
Figure 11. Steel frame impact simulation and impact direction on plane condition

Figure 11 shows the collision of the truck to the exterior and corner column of the 3D analysis model, and the analysis results for car speed of 120km/h are shown in Fig. 12. It is observed that the bottom of the exterior column is completely separated from the joint at 0.03 second after the impact. After passing through the exterior column the car continues to move until colliding with the adjacent interior column at t-0.19 second. As in the 2D model, the car collision results in progressive collapse. The vertical displacement of the upper joint of the impacted column is shown in Fig. 12(a), where it can be observed that the vertical deflection oscillate after the first impact to the exterior column and keeps decreasing after the second impact to the interior column. Fig. 12(b) depicts the deformed second story floor plan with respect to the original configuration. It can be observed that due to the series of collisions the second story is displaced laterally in significant amount and many floor beams suffers moderate to severe damage based on the failure criteria of ASCE (1000) shown in Table 4. The deformed configuration of the structure at the final stage of analysis is shown in Fig. 12(c), where it can be observed that the first story columns of the two right-hand-side frames are severely damaged and the structure is significantly tilted. Fig. 13 depicts the collision analysis results of the structure subjected to the car impact to the corner column. The vertical deflections at the joints increase monotonically after the first impact as shown in Fig. 13(a), which implies that the structure collapses progressively due to the collision to the corner column. This can be confirmed by the deformed configuration of the structure depicted in Fig. 13(b), which shows that all the first story exterior columns in the right-hand-side frame are severely damaged and the exterior frame is collapsed. Compared with the results of collision to the exterior column shown in Fig. 12, the car collision to the corner column results in more severe damage to the impacted part of the structure.
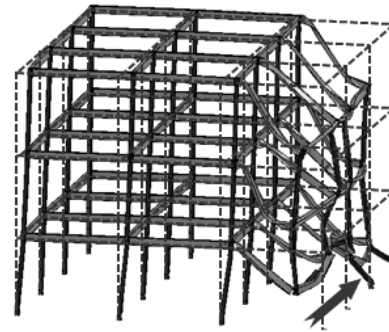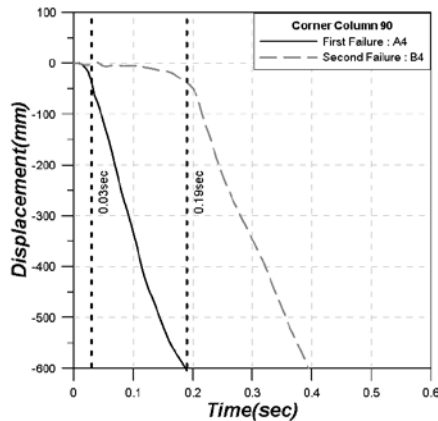

| (a) Vertical displacement of damaged joint | (b) Deformed structural plan (t=1.42sec) | (c) Damaged configuration (t=1.42sec) |

Figure 12. Analysis results for exterior column collision

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Table 4. Failure criteria for Steel members (ASCE, 1999)

Element	Material Properties	Failure Type	Criteria	Damage		
				Light	Moderate	Severe
Beam	Steel	Bending/ Membrane Response	δ / L	5%	12%	25%
		Shear	γ_v	2%	4%	8%
Column		Compression	$\Delta L / L$	2%	4%	8%

- δ / L : Ratio of center line deflection to span
- γ_v : Average shear strain across section
- $\Delta L / L$: Ratio of shortening to height

(a) Vertical displacement of damaged joint   **(b) Deformed configuration of the structure**
Figure 13. Analysis results for corner column collision

5. Summary

This study investigated the performance of a steel moment frame subjected to vehicle collision at a first story column using LS-DYNA. Nonlinear dynamic time history analyses were carried out with three bay 2D and 3D steel structures subjected to a car impact in a first story column with three different impact speeds.

The analysis results of the 2D frame and the 3D frame with collision to the exterior column showed that the model structure remain stable when the speed of the car is 40km/h. It was observed that only the exterior column was damaged before the car finally stopped. However at the speed of 80 and 120 km/h both the 2D and 3D structures were severely damaged by progressive collapse after the car pass 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 due to collision to the exterior column. It was also observed that the vertical displacement of the model structure caused by the automobile collision is significantly larger than that obtained by the arbitrary column removal method specified in the UFC (2013) provisions. Therefore the arbitrary column removal method applied to investigate the progressive collapse potential of a structure may underestimate the actual structural response for automobile collision.

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