**Damage Estimation of Steel Frame Buildings under Fire Using Collapse Analysis**

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Development of a fire in a steel frame building affects structural stability of the building with increase in temperature of structural elements exposed to fire. High temperatures of structural materials, such as steel or concrete, cause degradations of material strength and stiffness. These thermo-mechanical properties of structural materials would damage not only on structures of a building but also non-structural elements, e.g. exterior walls, compartment walls on/in the building because of large deformation of the structural elements. The behavior of the building exposed to fire generally results in falling and scattering of building components on the ground near the building.

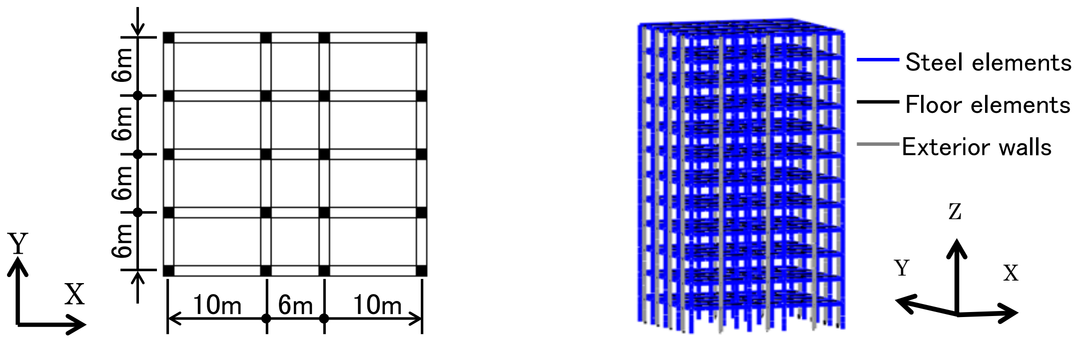
The objective of this research project is to propose an evaluation method for the relation between damage of building's structures and non-structural elements in a fire. To ensure the fire safety of buildings in fire resistance design, it is essential to clarify the damage by a fire. This research focuses on the behavior and scattered range of exterior walls on a building exposed to fire, which represents non-structural elements of a building, because falling of the walls affects safety of evacuees and firefighters around the building.

A modified ASI-Gauss technique [1], which included a computational algorithm for degradations of structural materials at high temperatures, was used to conduct fire response analysis for interactions between steel frame structures and exterior walls of a building in this research. Figure 1 showed the floor plan of 12-storey steel frame building for the fire response analysis. The specification of the building was listed in Table 1. The dimension of the building was 48 m high, 24 m wide (4-bay) and 26m long (3-bay). Steel grade of the structures was SS400 (mild steel). The building's structure was designed for appropriate seismic capacity with a typical base-shear coefficient ($Cb$ = 0.167). Autoclaved aerated concrete panel (AAC) and fastening method of AAC was also modeled as exterior walls in the analysis. Criteria for detaching a wall from structures were that the rotation angle of the wall exceeded 1/20 in in-plane or out-of-plane deformation shown in Figure 2 and 3 [2].

Fire responses of the 12-storey steel frame building with exterior walls in various fire cases shown in Table 2 were analyzed. A fire in the building was simply simulated by neglecting varieties of fire spread in the building, non-uniform fire heating, thermal conduction form heated elements to adjacent elements and so on. Increase in temperature of structures in a fire compartment was considered as one of the effects of fire exposure. Thermal expansion of structural elements, degradations of elasticity and yield strength of materials in Figure 4 were also implemented [3].

As a result of fire response analysis, it became obvious that falling of exterior walls was caused by large deformation of local elements even if damage of the whole building was not severe. Figure 5 showed the horizontal distance of scattered building elements from the edge of the building. Empirical model [4] for estimating scattered range of exterior tiles and three curves based on projectile motion with different horizontal velocities were also drawn. Building elements located in high altitude have a high possibility of scattering farther from the building. The calculated curve of projectile motion with horizontal velocity 4.0 m/s was able to cover almost all data obtained from the analysis. The empirical model also provided approximate values for the maximum distances of the analysis and Ronan Point Apartment Tower Accident [5]. It was found that horizontal velocity of elements was induced by contact and rebound motions between building components in many cases.

Figure 6 showed typical deformation type of structures in a fire. We estimated the damage of structure by 4 types of deformation: Slant angle of beams (1) and deflection at midpoints of beams (2), contraction of columns (3) and bending deformation of columns (4). Figure 7 showed the relation between steel temperature and degree of damaged elements *Nd*/*Nt.* Here, *Nd* was the number of deformed elements or detached walls. *Nt* was the total number of elements above fire floor. The number of detached walls correlated strongly with $D_{bs}$. On the other hand, $D_{bd}$ did not influence on the damage of walls. In general, the severe damages of outer columns and beams affect largely to the fall of exterior walls; however, some exceptions where severe damages of inner structure affect the fall of exterior walls were observed.

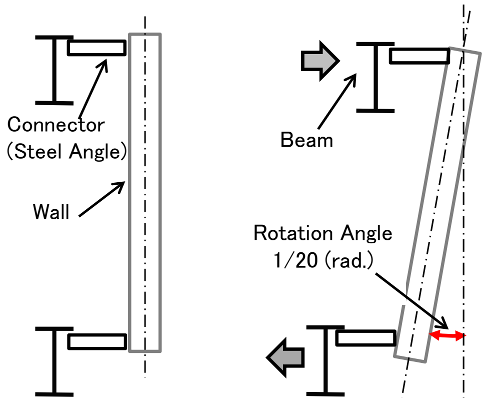



a) Floor plan and dimension  b) Arrangement of structural elements and walls

Figure 1 Structural model of steel frame building

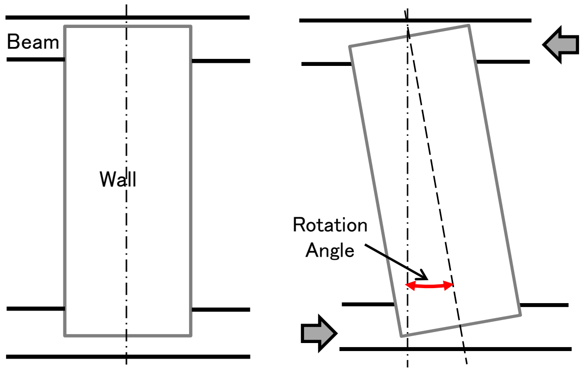
Table 1 Specification of steel frame building and components

| | |
|---|---|
| Floor number, Floor height | 12 stories, 4m |
| Total floor load | 800 kg/m$^2$ |
| Base-shear coefficient | *Cb*=0.167 |
| Steel grade | Mild Steel(SS400, JIS G 3101) |
| Exterior wall | Autoclaved aerated concrete panel |
| Dimension | 600 mm x 125 mm x 4.0 m |
| Fastening method | Rocking mechanism with bolts and steel plates |
| Floor Slab | Reinforced concrete |
| Thickness | 150 mm |




a) Original state b) Displaced state

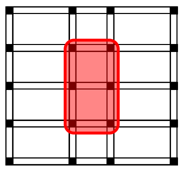
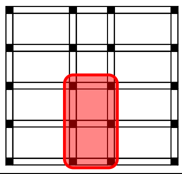
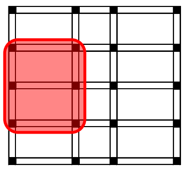
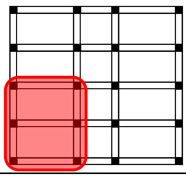
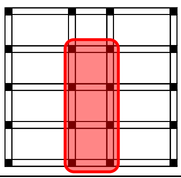
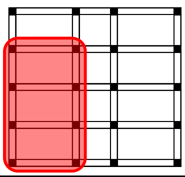
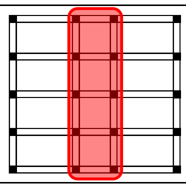
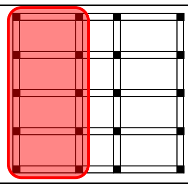
Figure 2 Out-of-plane displacement




a) Original state b) Displaced state

Figure 3 In-plane displacement

Table 2 Analyzed cases (Location and area of a fire in a single floor)

| Fire floor | 1, 2, 4, 6, 8, 10, 12F | | |
|---|---|---|---|
|  |  |  |  |
| Case - 2Ii | Case -2Io | Case -2Oi | Case -2Oo |
|  |  |  |  |
| Case -3I | Case-3O | Case- 4I | Case -4O |

*Areas in red show fire rooms in which structural elements increase in temperature.

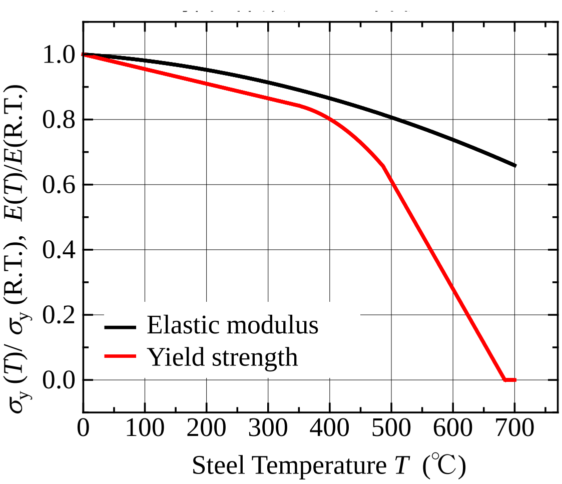



Figure 4 Residual mechanical properties at high temperatures[2]

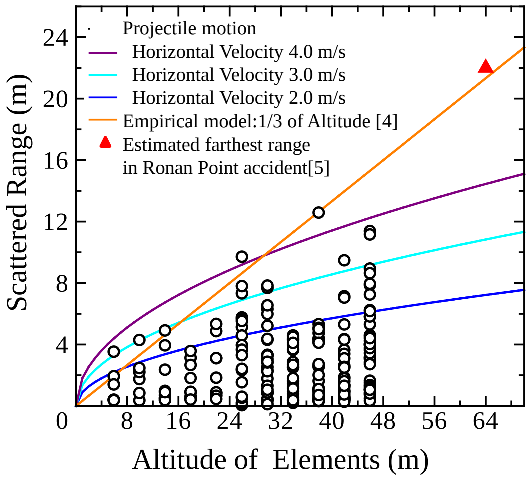
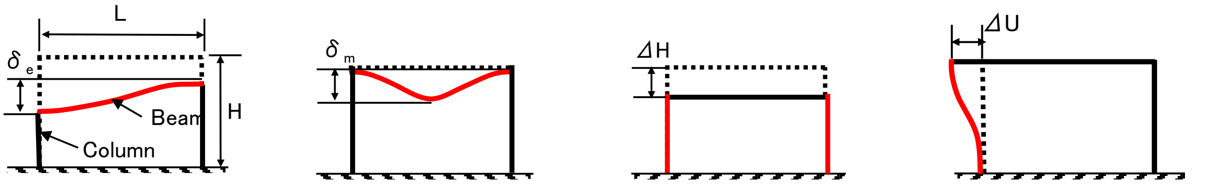



Figure 5 Relation between scattered range and altitude of building elements [4, 5]



a) Slant angle b) Deflection c) Contraction d) Bending deformation

Figure 6 Deformation of structural elements

| | | |
|---|---|---|
| Slant angle of beams | $D_{bs} = \delta_e/L$ | (1) |
| Deflection at midpoint beams | $D_{bd} = \delta_m/L$ | (2) |
| Contraction of columns | $D_{cc} = \Delta H/H$ | (3) |
| Bending deformation of columns | $D_{cb} = \Delta U/H$ | (4) |

Where $L$ and $H$ are length of the beam and height of the column respectively; $\delta_e$ is displacement of the beam in Figure 5; $\delta_m$ is deflection of the beam; $\Delta H$ and $\Delta U$ are contraction and deflection of the columns respectively.

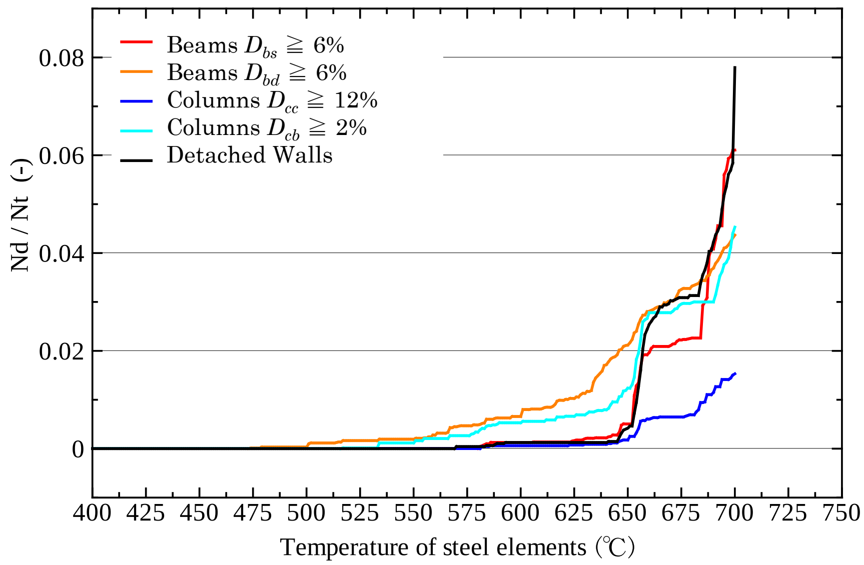


Figure 7 Temperatures of steel elements and degree of damaged elements

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