A Study on the Collapse Control Design Method for High-Rise Steel Buildings

Akira Wada, Prof., Tokyo Institute of Technology, Japan; **Kenichi Ohi,** Prof., Kobe University, Japan; **Hiroyuki Suzuki,** Prof., Tsukuba University, Japan; **Mamoru Kohno,** Head, Building Dept., National Institute for Land and Infrastructure Management, Japan; **Yoshifumi Sakumoto,** Dr, General Manager, Nippon Steel Corporation, Japan

Summary

Two direct causes led to the collapse of the World Trade Center (WTC) on September 11, 2001: column damage caused by aircraft crash, and the resulting large-scale fires. In spite of this damage, the towers remained standing after the crashes for 102 and 56 minutes, respectively, during which many lives were saved. The collapse of the WTC, however, may be taken as an alert that local failures can trigger a progressive collapse. It was also a landmark event since it alerted construction engineers about the importance of preventing progressive collapse in similar structures.

Prevention of progressive collapse requires the development of design technologies for frames that have high redundancy. This paper presents a new collapse control design method for high-rise steel building structures. The basic concept of the present collapse control design method is to save human lives. It proposes how to assess and improve the redundancy of structures by assuming the loss of structural members due to hazards.

Introduction

The British Standards and Building Standards [1] were the first to incorporate the prevention of progressive collapse in design standards. The incorporation of measures against progressive collapse was based on proving through experience, and was made to prevent the kind of progressive collapse attributed to a gas explosion in 1968 in a 22-storey high-rise residential building in Ronan Point, United Kingdom. Further, in the Building Standards of New York City (NYC Standards) established in February 2003, the following recommendation was made regarding the prevention of progressive collapse such as, the WTC collapse.

Recommendation 1: "Publish structural design guidelines for optional application to ensure robustness and resistance to progressive collapse."

Meanwhile, studies are now underway along with extensive discussions in a variety of related fields regarding the development of a simple, practical design method. In order to suppress progressive collapse, it is necessary to develop a technology for designing frames with high redundancy. With this in mind, a Committee to Study the Redundancy of High-Rise Steel Buildings within the Japanese Society of Steel Construction was established by the Japan Iron and Steel Federation. This Committee has carried out the following studies aimed at improving the safety of high-rise buildings:

- a study of collapse control design methods based on seismic- and fire-resistant technologies used in Japan and;
- a study to quantify the redundancy of high-rise steel buildings in Japan aimed at producing a frame with high redundancy.

In this paper, findings obtained from the collapse of the WTC are described and a method to prevent progressive collapse is examined. Further, a collapse control design method that can prevent the occurrence of progressive collapse is outlined.

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Findings from WTC Collapse

In order to structure a progressive collapse control design method for high-rise buildings with higher redundancy, the Committee to Study the Redundancy of High-Rise Steel Buildings inferred the causes of the WTC collapse with reference to the available literature [2] and then outlined its findings. It is understood that in cases where vertical load support members are lost due to unassumed loads or accidents and where vertical load supporting members lose functionality due to large-scale fire, it is important to provide measures whereby local collapse do not lead to entire collapse. To achieve this goal, it is necessary to increase vertical load redistribution capacity by providing back-up systems for multiplying the number of loading routes. Further, it is necessary to secure the plastic deformation capacity and fire resistance of the steel members and joints used.

Assessment Method

Setting Targets

Generally, it is difficult and uneconomical to conduct structural design by assuming accidental loads due to hazards. Accordingly, in contrast to conventional methods, the present design method assesses and improves the redundancy of buildings by assuming the loss of structural members such as columns and beams due to accidents and assesses how many members might be lost and the probability of occurrence of an entire collapse.

Since it is fair to expect that fire compartments will break and that fire will spread in both planar and vertical directions, it is necessary while estimating member loss to pay attention to the effect (increasing the degree of loss) that fire will have. Based on the above, designers discuss whether or not a structure is designed both in terms of structure and fire resistance to compensate for the loss of members and whether or not collapse control design is to be applied. When collapse

control design is used, the key-element members are specified in the frame design according to an assessment flow as described in the following paragraph. Priority is given to protecting the key-element members so as to improve building redundancy.

Assessment Flow

Fig. 1 shows an outline of assessment flow. In the following, the present collapse control design method is explained in terms of assessment flow.

Assessing Risk and judging whether or not to use Collapse Control Design

In the present design method, the effect of unexpected loads caused by terrorist explosions and aircraft crashes are not assessed directly as accidental loads, and are not reflected on the design. However, losses or declines in the yield strength of vertical load supporting members that are brought about by the application of unexpected loads are assessed and are reflected in the design work.

Based on the concept that improving the redundancy of buildings minimizes the risk of a progressive collapse, the present design method aims at compensating for loss or decline in the yield strength of members that support vertical loads. In the initial design stage, structural designers judge whether or not to apply the collapse control design method, taking into account the risk of explosions and airplane crashes in the building under consideration. Buildings exhibiting limited risk do not require a collapse control design method; for them, a conventional design method is selected.

Further at this stage of design, the potential scale of column member loss is assumed by taking into account the degree of risk involved and importance of the building, that is the effect it would have in the case of collapse. The standards [1] prescribe the prevention of progressive collapse even in the case of one column being lost. In cases where the design of a building requires more appropriate redundancy, it is desirable to determine in the design the number of columns to be lost. More practical determination of the members to be lost can be made after fixing the sectional dimensions of the members by means of conventional structural and fire-resistant design methods.

Basic Design

The basic design work takes into account the scale of the members to be lost. At this stage, it is important to proceed with the design work in collaboration with structural engineers and architects, as well as fire engineers. Although conventional design work assumes cooperation between structural engineers and architects and between architects and fire engineers, adequate cooperation between structural and fire engineers has been lacking. More practically, because the arrangement of the core by architects and the selection of the frame system and the arrangement of columns by structural engineers are deeply related to the arrangement of fire separations and the selection of fire protection, the present design method requires the design work to be carried forward by accepting suggestions offered by fire engineers.

In order to enhance the redundancy of high-rise buildings, it is important to

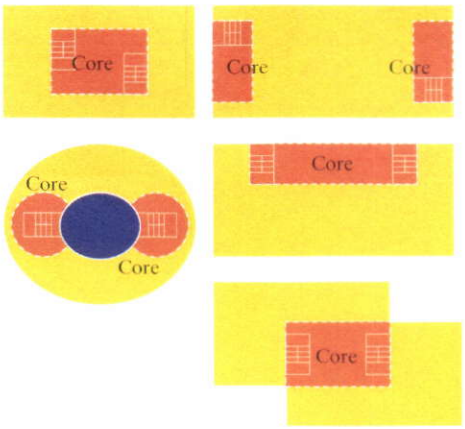


Fig. 2: Typical core arrangement

secure vertical evacuation routes or to re-arrange the core and safeguard the core inside. *Fig. 2* shows a typical core arrangement. It is desirable to separate and symmetrically arrange stairway locations so as to raise the probability of being able to secure evacuation routes. It is understandable that well arranged cores offer higher redundancy. Further, it is desirable to structure the fire compartment with materials having excellent impact resistance and fire resistance in order to prevent fire from spreading into the core section.

During basic design, the selection of the frame system parallels the arrangement of the core. *Fig. 3* shows frame deformation after the loss of three columns on the first floor in various frame systems (identical cross sections for all columns and beams) [3]. In the analysis, the vertical load is applied so that the axial force ratio becomes 0,35. As shown in *Fig. 3*, in cases with the functional loss of three columns (except for the moment resistant frame (MRF) structure (a)), the frame does not suffer entire collapse although it does experience local collapse on certain floors. This shows that braces installed to provide resistance against wind and seismic loads are effective in redistributing vertical loads. To this end, it is desirable to select a frame system that will have a high load redistribution capacity after the functional loss of vertical load supporting members.

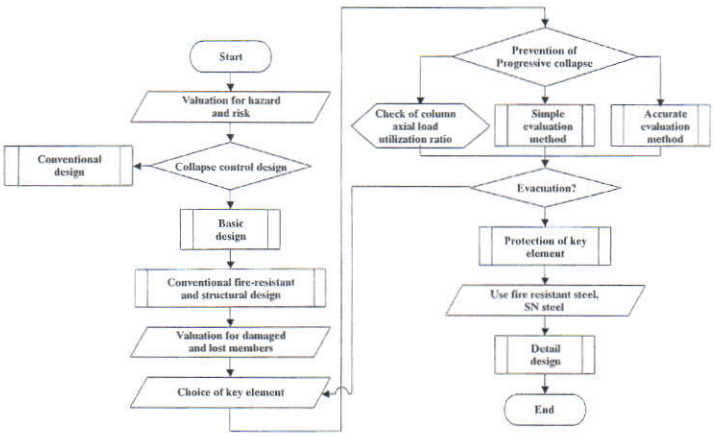


Fig. 1: Outline of recommended flow of collapse control design

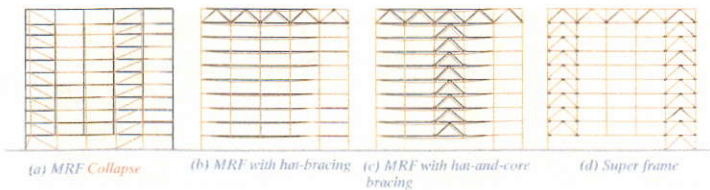


Fig. 3: Analysis results for various frame systems at time of column loss: (a) MRF (Moment Resistant Frame) Collapse (b) MRF with hat-bracing (c) MRF with hat-and-core bracing (d) Super frame

Selection of Members to be Lost and Key Elements

After completion of the basic design, the cross section of the members is chosen in conformity with conventional structural and fire design. In the present design method, the concept of key elements is applied as a means to improve cost-effective redundancy in a manner that conforms to standards [1].

When the cross section of the members is chosen in conformity with conventional structural design, the members to be lost are determined and the key elements are selected. The members to be lost are determined taking into account the scale of a potential explosion and the risks involved. At this stage, the key elements can be excluded from the members to be lost on the premise that they will be reasonably safe because they are protected with every measure available. In the present collapse control design method, the determination of key elements is cited as an important requirement. The key elements are those members whose loss directly affects the risk of a chain-reaction collapse; thus, the specifications for fire protection and others are fixed so as to secure the greatest possible safety against unassumed loads. According to the analytical results [3, 4], it is known that the loss of corner columns is the severest cause of reduced vertical load supporting capacity. Accordingly, it is desirable to set the corner columns as key elements and to adopt for them methods and materials conducive to improving redundancy, such as fire resistant (FR) steel and the blanket-type fire protection introduced below. In selecting the key elements, they are to be arranged in a concentrated manner such as selecting only corner columns, providing the chosen columns with sufficient excess yield strength (axial force ratio of columns) so that they alone can support the loads on all floors, or possibly selecting every third column as a key element. In setting the key elements, it may be effective to use the sensitivity analysis in [5].

Prevention of Chain-Reaction Collapse

After setting the key elements, an assessment regarding the prevention of chain-reaction collapse is made. There are three assessment methods: assessment using only the axial force ratio of columns, simple assessment and detailed assessment.

Assessment using only the Axial Force Ratio of Columns

While conducting an assessment that uses only the axial force ratio of columns, the axial force ratio of columns is checked at the earliest stage when the loss of vertical load supporting members is not taken into account; this is done to improve qualitative safety. It is known from the analyses in [4, 6] that the use of axial force ratio of columns during stationary vertical loading is effective as a simple assessment method for preventing chain-reaction collapse. When vertical load supporting members are lost, the vertical load is redistributed to other vertical load supporting members via beams, outrigger trusses and hat braces. Generally, these members are arranged in designs as wind and seismic-resistant members, but when vertical load supporting members are lost, they function as vertical load redistribution members. In cases where a certain surplus exists in the working axial force ratio of columns, these members have a surplus capacity for supporting redistributed vertical loads. Accordingly, as shown in Equation (1), improvements in redundancy are enhanced by setting a critical value for the axial force ratio and suppressing the maximum value of the axial force ratio of columns, n_{max}, to a level below the maximum value.

$$n_{max} < n_{limit} \tag{1}$$

In this paper, the maximum value is set at $n_{limit} = 0{,}25$, based on the analytical results [3, 4].

Simple Assessment

Simple assessment is a method to check the load redistribution capacity of columns and beams at the moment when vertical load supporting members are lost.

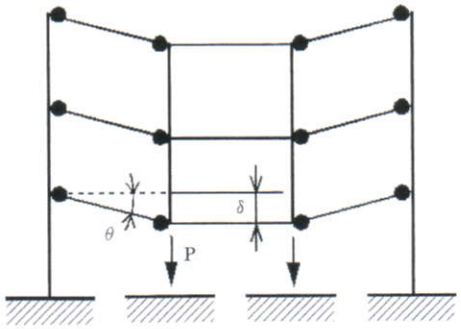


Fig. 4: Simple assessment of the vertical load supporting capacity of beams

First, a simple check is made of the vertical load redistribution capacity of the beam shown in *Fig. 4*; when needed, vertical load redistribution members are arranged. The vertical load redistribution capacity is checked with Equation (2).

$$\sum_{j=1}^{n} P_j < \sum_{j=1}^{N} \frac{{}_b M_{pi}}{L} \tag{2}$$

The left-hand side indicates the total sum of axial forces of columns and the right-hand side the total sum of the shear force of the adjoining beams. In cases when Equation (2) is not satisfied, vertical load redistribution members such as outrigger braces and hat braces are provided to compensate for the shortage of axial force.

Next, as shown in *Fig. 5*, the axial force borne by columns assumed to be lost is uniformly borne by the two columns adjoining those that were lost; the axial force ratio, n_r, thus obtained is checked employing Equation (3).

$$n_r < n_{r\bullet limit} = 1{,}0 \tag{3}$$

Detailed Assessment

Further, in cases when a detailed assessment is to be conducted, members such as columns are removed and a static incremental analysis is made employing a plane frame or

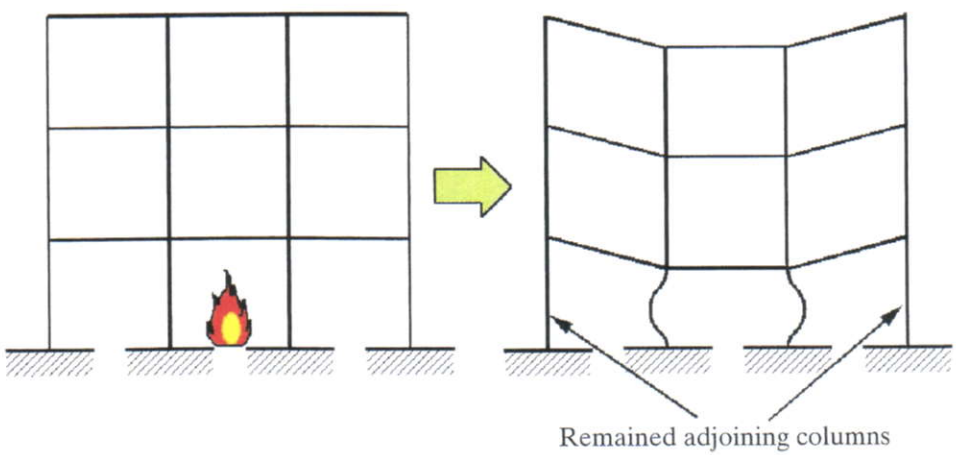


Fig. 5: Assessment of the loading capacity of remaining adjacent columns

three dimensional frame following a simple assessment. In cases involving more complex frames and likewise, a detailed analysis is conducted depending on the judgment of the designers.

Fig. 6 shows the result of a nonlinear static incremental analysis made for the loss of twentieth floor interior columns in a 27-storey office building with 6,4 m column grids and 17,5 m long-span girders. The frame was stable after the loss of seven corner columns. Plastic hinge occurred at each end of the girders on the upper floors, which formed a beam sidesway mechanism. In the next step, the frame became unstable after the loss of eight corner columns. For more details, please refer to [4, 6].

Protection and the Detail Design of Key Elements

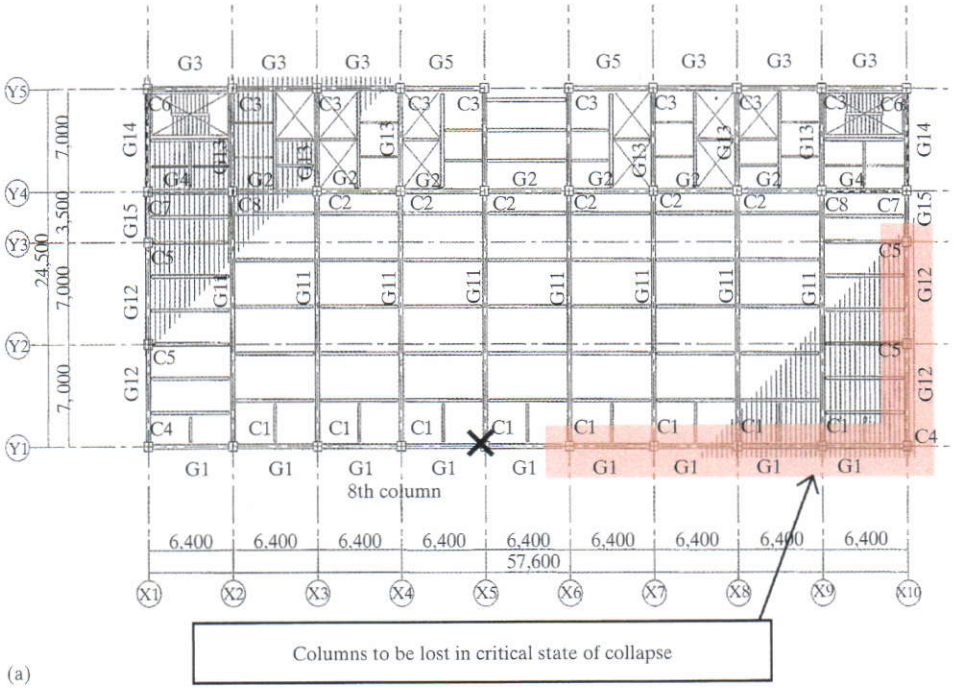
Due care is paid to protecting the key elements so that they are not lost. Further, it is desirable to adopt materials and methods (such as fire resistant (FR) steel and blanket-type fire protection) for the key elements that help to increase redundancy in the sections where they are located.

The detail design stage includes the design of beam-column connections, the design of floor systems, the design of fire separations and connection details, and the determination of fire protection specifications. As stated above, in order to meet emergency conditions that arise due to loss of structural members, application of connection with load-carrying capacity for the joining of beams to columns and columns to columns has become an important element in securing the deformation capacity of members, realizing the integration of floor systems and ensuring the fire resistance of key elements.

Materials and Methods Effective in protecting Key Elements

Finally, brief descriptions are given for fire resistant (FR) steel representative material effective in protecting key elements and of fire protection that offers excellent impact resistance.

Transition in yield strength of FR steel and convention steel due to temperature is shown in *Fig. 7*. FR steel retains



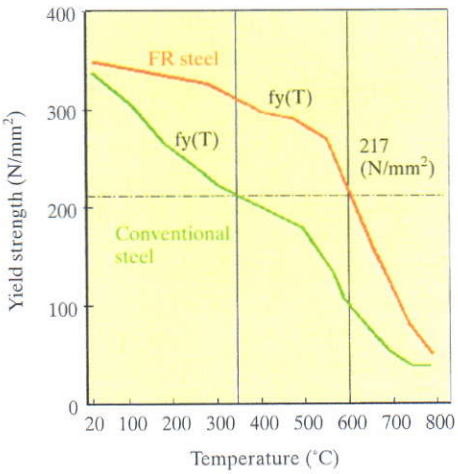


Fig 7 : Transition in yield strength of fire resistant (FR) steel and general steel due to temperature

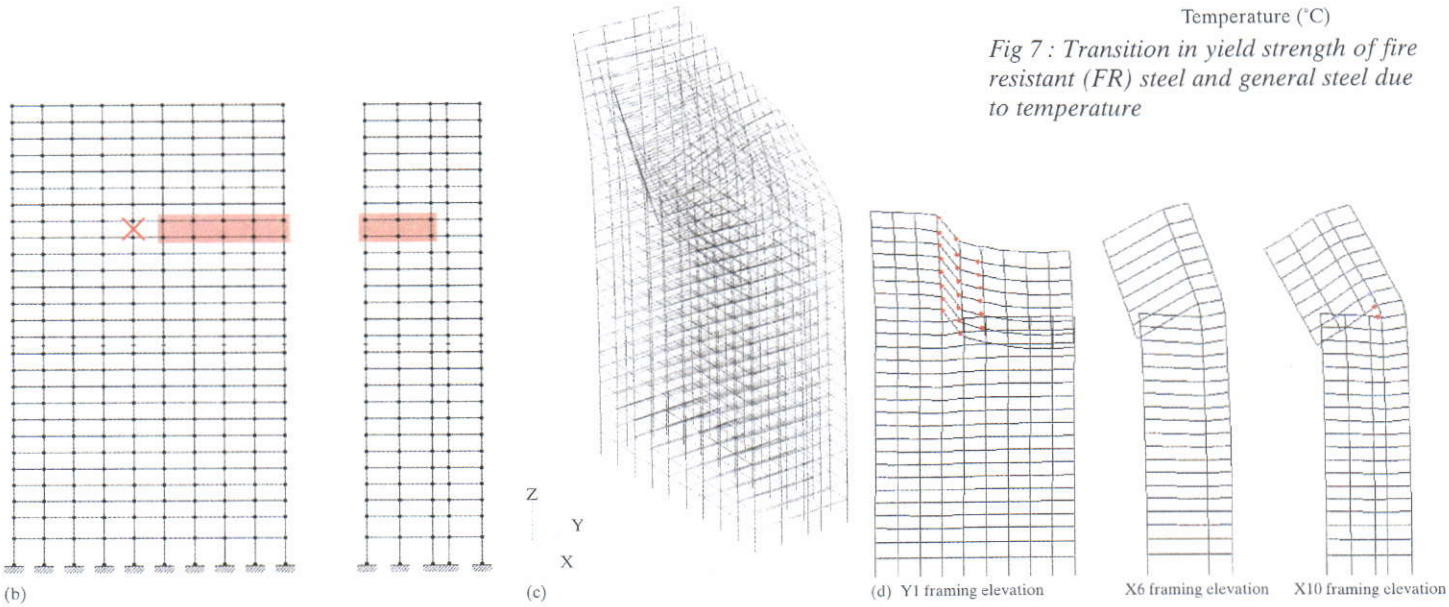


Fig. 6: Analysis results: distortion of frame (loss of 8 corner columns on 20th floor=Collapse)

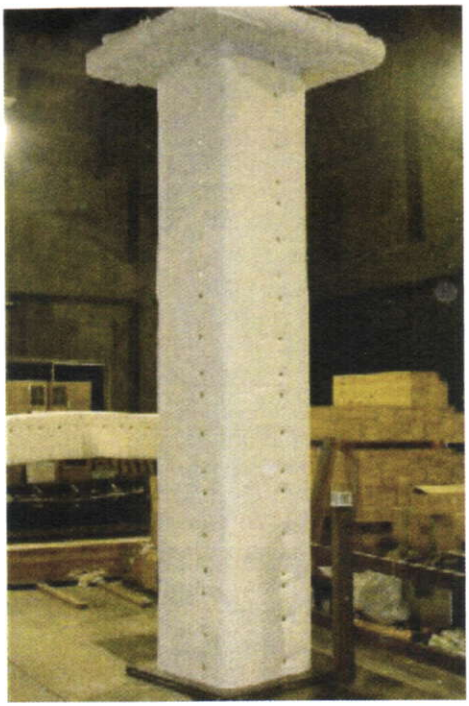


Fig 8: Blanket-type fire protection

more than two-third of its specified yield strength at room temperatures until 600 °C is exceeded; therefore, its application is effective in retaining the load supporting capacity of beams and columns during large-scale fires. *Fig. 8* shows blanket-type fire protection that has higher impact resistance than spray-type or dry board-type fire protection and provides effective protection against explosions too.

Conclusion

In this paper, findings obtained from the WTC collapse, and measures to prevent occurrence of progressive collapses were examined, and a collapse control design method was proposed. The proposed design method aims at increasing the redundancy of buildings by making assumptions regarding the loss of structural members and assessing the possibility of an entire collapse occurrence.

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