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

by

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## ABSTRACT

Two direct causes led to the collapse on September 11, 2001 of the World Trade Center towers: 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 towers, however, may be taken as an alert that local failures can trigger a progressive collapse. It was also a landmark event in that it alerted construction engineers to 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. The Japan Iron and Steel Federation together with the Japanese Society of Steel Construction established the committee on “The Study on Redundancy of High-Rise Steel Buildings” in June 2002 in an attempt to study and provide a better understanding on progressive collapse by collaboration with Council on Tall Buildings & Urban Habitat. This paper presents a new collapse control design method for high-rise steel building structures. The basic concept of the present collapse control design methods is to save human lives. Therefore, the method presented here to prevent progressive collapse until the completion of evacuation makes assumptions about which structural members are likely to be lost and proposes the idea of ‘key elements’ that are linked with a building’s core section to serve as the evacuation route and consist of structural members indispensable for supporting redistributed vertical loads.

KEYWORDS: Collapse Control Design, Key Element, Progressive Collapse

## 1. INTRODUCTION

The collapse of the World Trade Center towers (WTC1 and WTC2) was the direct result of column damage and large-scale fires caused by airplane crashes. In spite of this, WTC1 and WTC2 remained standing for 102 minutes and 56 minutes respectively, during which many lives were saved. The fact that so many lives were saved is reportedly due to the large deformation capacity or load redistribution capacity inherent in steel structures [1]. From this, it can be understood that the tower structures of the World Trade Center (hereinafter referred to as “WTC”) had a certain degree of redundancy. Nevertheless, the WTC collapse serves as a warning about progressive collapse triggered by a local collapse that causes an entire building collapse. It was a landmark event that alerted construction engineers to the importance of preventing progressive collapse in other similar buildings.

The British Standards and Building Standards [2] 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-story high-rise residential building in Ronan Point, United Kingdom. Further, in the Building Standards of

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New York City (NYC Standards) established in February 2003, the following recommendation was made regarding the prevention of progressive collapse such as that seen in 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, the Japan Iron and Steel Federation established the Committee to Study the Redundancy of High-Rise Steel Buildings within the Japanese Society of Steel Construction; 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.

## 2. 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 organized the causes of the WTC collapse with reference to the available literature [1] and then outlined its findings. Fig. 1 shows the study results for the cause of the WTC collapse. From this figure, it is understood that in cases where vertical load supporting members are lost due to unexpected loads or to accident and where vertical load supporting members lose functionality due to large-scale fire, it is important to provide measures whereby local collapse does 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, as shown in Table 1. Further, it is necessary to secure the plastic deformation capacity and fire resistance of individual steel members and joints between them.

High-rise steel buildings constructed in Japan using seismic-resistant design have surplus capacity vis-à-vis stationary vertical loads and employ connections with appropriate load-bearing capacity for the joints. Because of this, it is believed that vertical load redistribution capacity can be increased with minimal added cost. Further, as stated in the following, the application of SN steel (low yield-point high performance steel), fire-resistant (FR) steel and concrete-filled steel tube (CFT) structures facilitates improved plastic deformation capacity in remaining members when some columns are lost and during fire.

## 3. ASSESSMENT METHOD

### 3.1 Setting Targets

Fig. 2 shows the difference between the concepts employed in the present collapse control design (right) and those found in conventional structural and fire-resistant designs (left).

Generally, it is difficult and uneconomical to conduct structural design by assuming accidental loads due to extreme events. 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 assessing how many members might be lost and the probability of entire collapse occurring.

Because it is fair to expect that fire separations will break and that fire will spread not only horizontally but also vertically, it is necessary when 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 next section. Priority is given to protecting the key-element members so as to improve building redundancy.

## 3.2 Assessment Flow

Fig. 3 shows an outline of assessment flow. In the following, the present collapse control design method is explained in terms of assessment flow.

### 3.2.1 Assessing Risk and Judging Whether or Not to Use Collapse Control Design

When considering the probability of explosions and airplane crashes caused by terrorist attack, it is not always reasonable to incorporate the effects of such unexpected loads into an original design. Further, such a design approach offers the possibility of exceeding the allowable economic limits. It is also difficult to forecast the behavior of structural members and frames to accidental loads and to reflect the structural response in the design work commonly being undertaken.

In the present design method, the effect of unexpected loads caused by terrorist explosions and aircraft crashes is not assessed directly. Rather, 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 to compensate 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 exposed to limited risks may not require a collapse control design method; only a conventional design method will be selected in these cases.

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 the importance of the building, i.e. the effect it would have in the case of collapse. The British Standards and Building Standards [2] prescribe the prevention of progressive collapse even in the case of one column being lost. In cases when the design of a building requires more appropriate redundancy, it is desirable to determine the number of columns to be lost in the design. 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.

### 3.2.2 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-resistant design engineers. Although conventional design work assumes cooperation between structural engineers and architects and between architects and fire-resistant design engineers, adequate cooperation between structural engineers and fire-resistant design 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 that the design work be carried forward by accepting suggestions offered by fire-resistant design engineers.

In order to enhance the redundancy of high-rise buildings, it is important to secure vertical evacuation routes or to arrange the core and safeguard the core inside. Fig. 4 shows a typical core arrangement. It is desirable to distribute 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 construct the fire separation 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. 5 shows frame deformation after the loss of three columns on the 1st 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 the figure, in cases with the functional loss of three columns (except for the moment resistant frame structure), 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.

### 3.2.3 Selection of Members to Be Lost and Key Elements

After completion of the basic design, the cross section of the members is decided in conformity with conventional structural and fire-resistant design. In the present design method, the concept of key elements is adopted as a means to improve cost-effective redundancy in a manner that conforms to British Standards and Building Standards [2].

When the cross section of the members is decided 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 available measure. 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; the specifications of fire protection etc. of the key element are to be determined so as to secure the greatest possible safety against extreme actions.

According to the analytical results in Fig. 6 [3] and the analyses in References [3] and [4], it is known that the loss of corner columns is the greatest cause of reducing 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 FR steel, CFTs 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 strength (lower axial force ratio of columns) so that they alone could 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 Reference [6]. However, this method of analysis has not reached the point where it is always applied in conventional design work. Advances in simple analysis programs and other developments are expected in this field.

### 3.2.4 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.

1) Assessment using only the axial force ratio of columns

When conducting an assessment that uses only the axial force ratio of columns, a check is made of axial force ratio of columns 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 References [4] and [5] that the use of the 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, 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 limiting value.

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

In this paper, the limiting value $n_{\text{limit}} = 0.25$ is proposed, based on the analytical results in [3] and [4].

2) 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.

First, a simple check is made of the vertical load redistribution capacity of the beam shown in Fig. 7; when needed, vertical load redistribution members are arranged. The vertical load redistribution capacity is checked with the following equation [4].

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

The left-hand side indicates the total sum of axial forces supported by the lost columns and the right-hand side the total sum of share capacity of the adjoining beams. In cases when the above equation is not satisfied, vertical load redistribution members such as outrigger braces and hat braces are provided to compensate for the shortage of the beam capacity.

Next, the total axial force borne by the columns assumed to be lost is redistributed evenly to the adjoining two columns as shown in Fig. 8; the axial force ratio thus obtained is checked by the following equation.

$$n_r \le n_{r \cdot limit} = 1.0 \tag{3}$$

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 of planar or three-dimensional frames is carried out following the simple assessment. In cases involving more complex frames etc., a detailed analysis is conducted depending on the judgment of the designers. For more detail, the readers should refer to [4] and [5].

3.2.5. Protection and the Detail Design of Key Elements

Due care is paid to protect the key elements so that they are not lost even in extreme events. Further, it is desirable to adopt materials and methods (such as FR steel, CFTs and blanket-type fire protection) for the key elements that enhance 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 because of the loss of structural members, adopting connections with sufficient load-carrying capacity for joining beams to columns and columns to columns is important element in securing the deformation capacity of members, realizing the integration of floor systems and ensuring the fire resistance of key elements.

## 4. MATERIALS AND METHODS EFFECTIVE IN PROTECTING KEY ELEMENTS

Finally, brief descriptions are given of FR steel and unprotected CFT structures—representative materials and methods effective in protecting key elements—and of fire protection that offers excellent impact resistance.

Fig. 9 shows the temperature-induced transition in yield strength of FR steel and general steel. FR steel retains more than 2/3 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. 10 shows the results of loaded fire-resistance tests for unprotected CFT (Fig. 11). The figure clearly indicates that in cases of axial force ratios at 0.25 or under, unprotected CFT structures can withstand loading for more than 3 hours. A blanket-type fire protection, as is in Photo 1, generally has higher impact resistance than spray-type or dry board-type fire protections and also provides effective protection against explosions.

## 5. CONCLUSIONS

Findings obtained from the WTC collapse and measures to prevent progressive collapse were examined and a collapse control design method was proposed. The present 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 occurring.

“Guidelines for Collapse Control Design” (Japanese and English versions) were published in two volumes [7, 8] and supplementary volume (English version only) [9] by the collaborative effort of The Japan Iron and Steel Federation and Council on Tall Buildings & Urban Habitat.

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Table 1　Measures to Prevent Progressive Collapse

- Increase of load transfer (and evacuation) routes·
- Increase of load redistribution capacity·
- Securement of plastic deformation capacity (members and materials)·
- Increase of connection strength (connection with load-carrying capacity)·
- Selection of fire protection materials·
- Securement of fire resistance of structural members proper (members and materials)

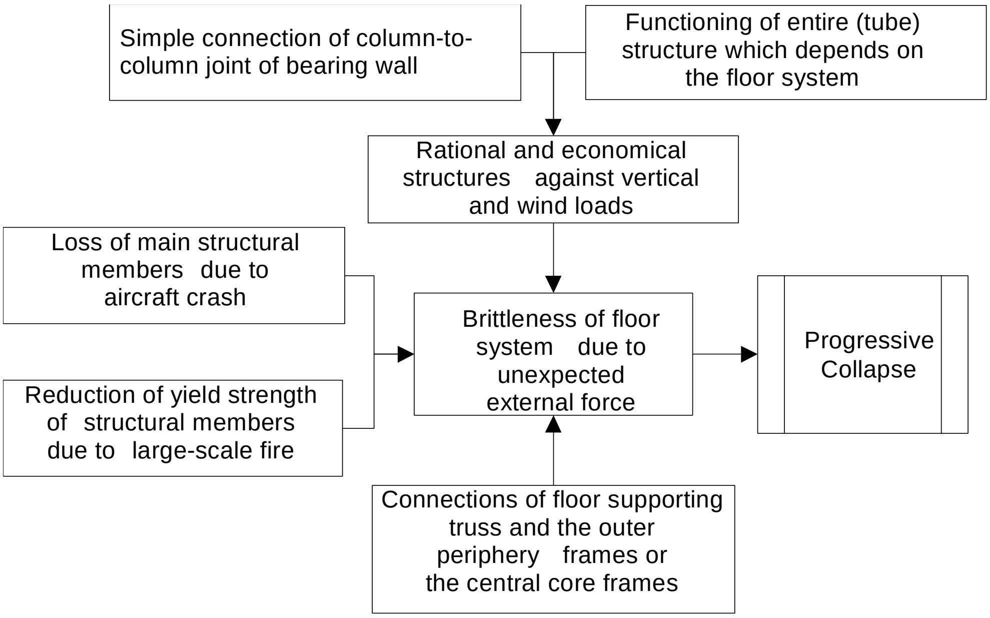


Fig. 1　Analysis of Causes of WTC Collapse

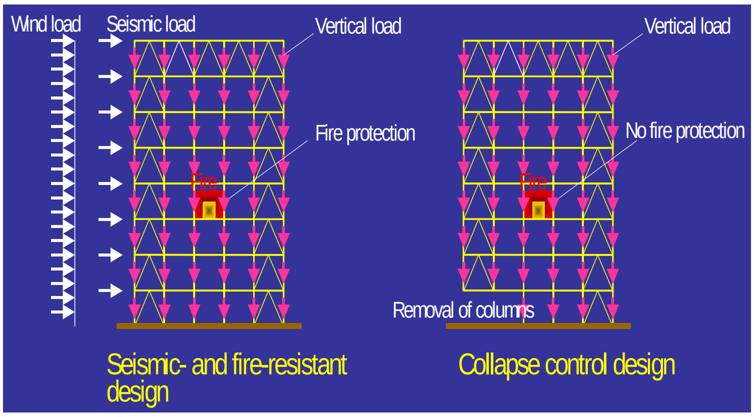


Fig. 2 Image of Collapse Control Design

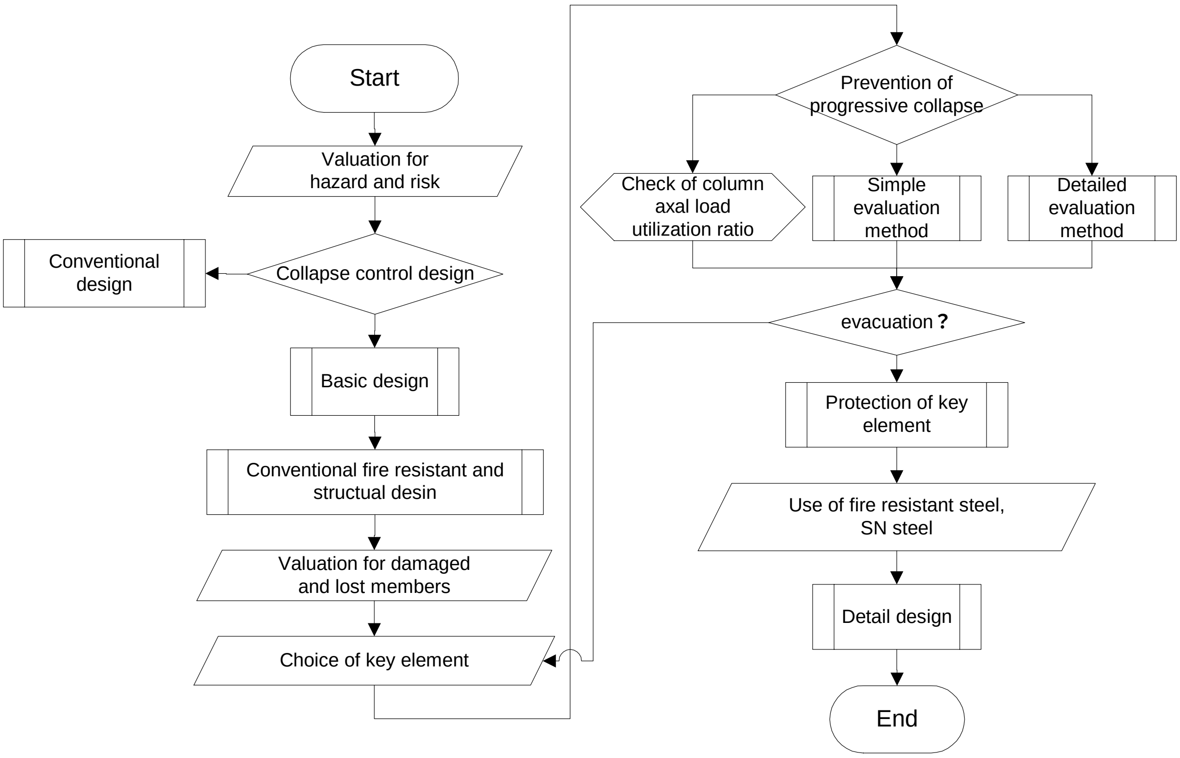


Fig. 3 Outline of Recommended Flow of Collapse Control Design

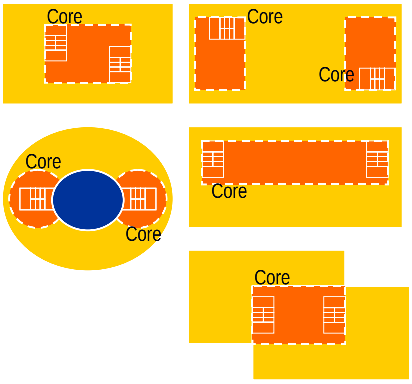
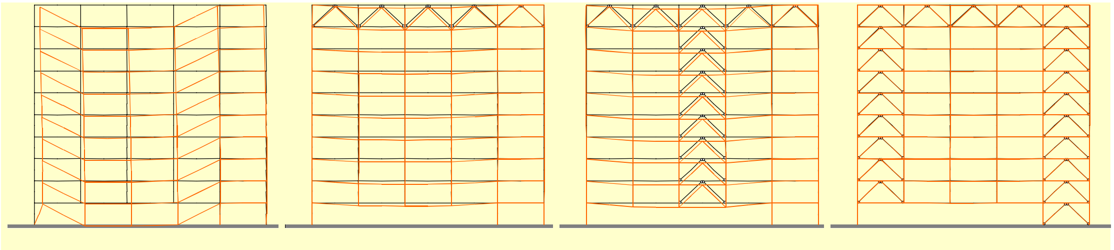


Fig. 4 Typical Core Arrangement



(a) MRF

(b) MRF with hat-bracing

(c) MRF with hat -and-core bracing

(d) Super frame

Fig. 5 Analysis Results for Various Frame Systems at Time of Column Loss

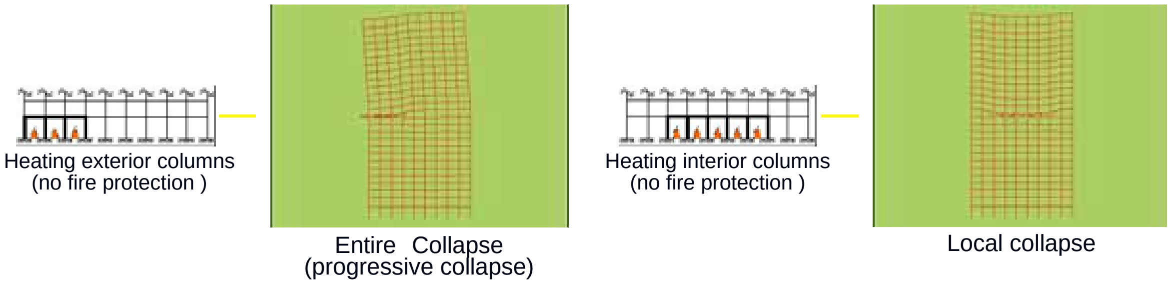
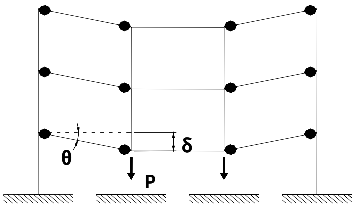


Fig. 6 Analysis Results for Thermal Elasto-Plasticity and Buckling during Fire



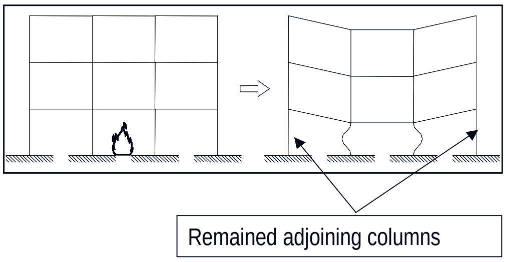
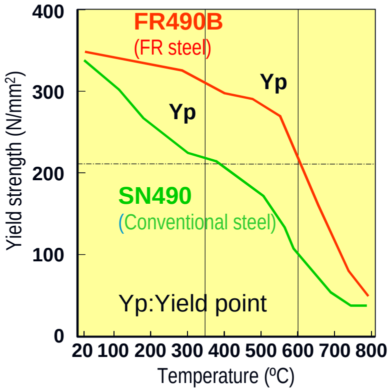


Fig. 7 Simple Assessment of the Vertical Load Supporting Capacity of Beams

Fig. 8 Assessment of the Loading Capacity of Remaining Adjacent Columns



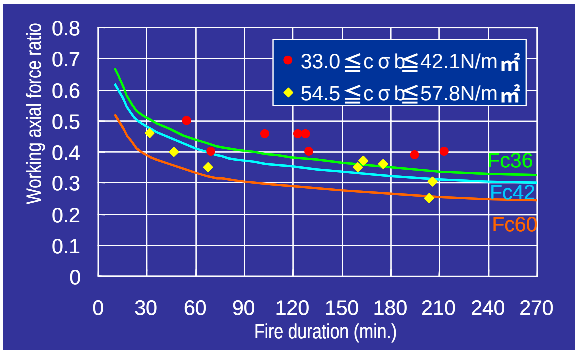


Fig. 9 Transition in Yield Strength of FR Steel and General Steel due to Temperature

Fig. 10 Heated Loading Test Results for Unprotected CFT Column

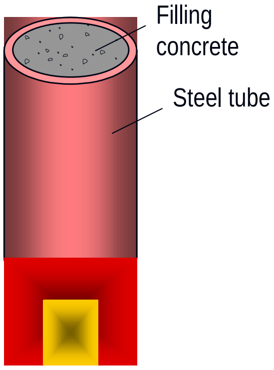


Fig. 11. Unprotected CFT Column

Photo 1. Blanket-type Fire Protection

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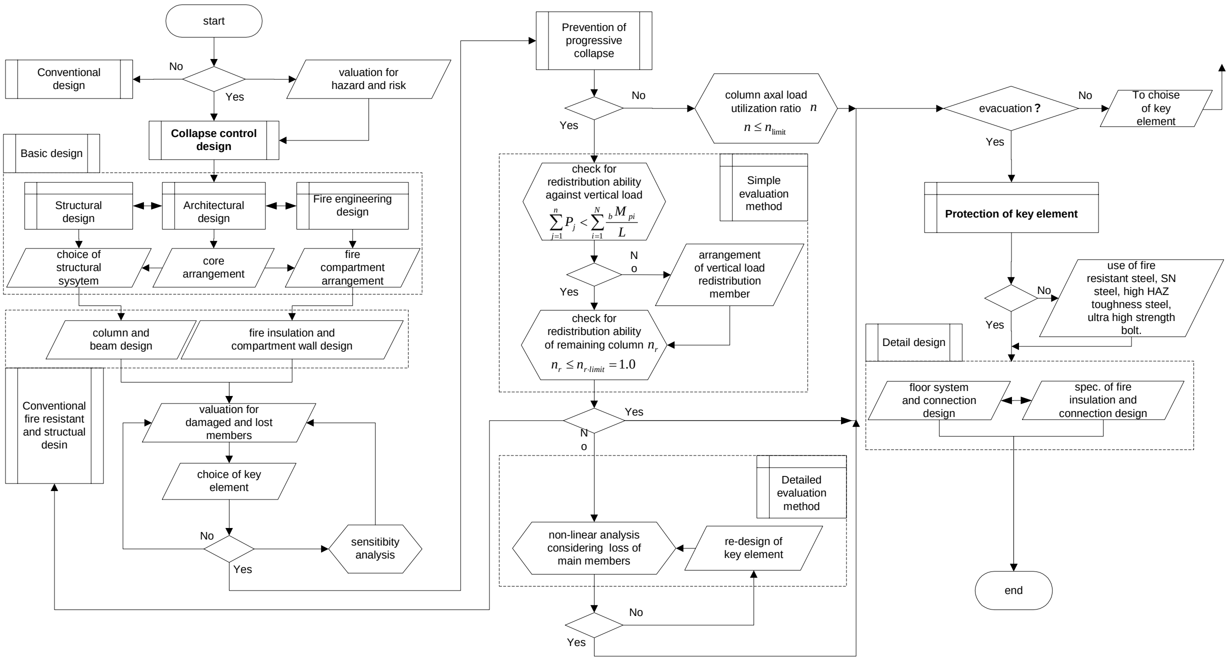

Fig. 12 Flow of Collapse Control Design (Detail)