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Publisher's version / Version de l'éditeur:

[https://doi.org/10.1061/41130\(369\)118](https://doi.org/10.1061/41130(369)118)

Structures Congress 2010: Proceedings of the 2010 Structures Congress, May 12-15, 2010, Orlando, Florida, pp. 1299-1309, 2010-05-01

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NRCC-52717

Mostafaei, H.

January 2010

A version of this document is published in / Une version de ce document se trouve dans:
The Structural Engineering Institute's 2010 Structures Congress Joint with the
North American Steel Construction Conference, Orlando, Florida, May 12-15,
2010, pp. 11

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A Simple Approach for Performance Evaluation of Structures in Fire

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ABSTRACT

A simple performance-based test technique was developed for the fire resistance assessment of columns. In this method, the column specimen is tested using a conventional column furnace while it is coupled with a simple analytical model. The simplified model simulates the remainder of the building. The components of interaction between the column specimen and the analytical model are deformations and loads. The new test approach includes the axial load-deformation interaction components. In other words, the axial load of the column specimen is varied according to the structural system response. The simple approach was employed for different building frames and the results were compared and verified with those obtained from an analysis using the SAFIR computer software. This paper provides the theoretical concept and formulation of the simple hybrid test approach. Before putting the model in practice, it will be further verified through a future experimental program.

INTRODUCTION

Fire resistance testing provides a means of determining whether or not the building materials or elements meet minimum performance criteria as set out in the building codes. Traditionally, fire resistance ratings of building elements have been measured using the prescriptive test method, basically by assessing individual elements with no consideration to the interaction between a structural element and the structural system of the whole building. In other words, building elements such as beams and columns are tested separately from other building elements. Research has determined that the column load does not remain constant under high temperature. In fact, the load is greatly increased. Hence, a practical fire safety design of buildings requires assessment and testing of structures based on the performance of the whole structural system. To this direction, this paper explores a new, simple, experimental technique to test the fire resistance of building columns with consideration of the effects from the structural systems. Further details of the new method, including numerical

examples for reinforced concrete and steel building frames, have been provided in two research reports previously published by the National Research Council Canada (Mostafaei and Mannarino, 2009 and Mostafaei and Hum 2009).

CONCEPT OF THE NEW TEST METHOD

Figure 1 illustrates the new simple fire test technique. It includes computer software or a simplified analytical model, and a column furnace test facility. The analytical tools model the entire building frame, except the column specimen, to determine the load-deformation interaction components between the column and remainder of the building. In this study, the simplified analytical model was developed and the computer structural engineering software, SAFIR, was implemented to verify the analytical results.

The analytical models are defined as load-deformation relations. The axial and lateral load-deformation curves are determined according to the axial and lateral thermal expansion of the structure. For this study, only the axial load-deformation relation is determined by the analytical process. Therefore, the column is fire tested under variable axial load. The value of the axial load is determined according to the frame stiffness calculated by the analysis. This process can be implemented in real time to feed back the test results into the analysis with the new mechanical properties at a given temperature of the column obtained from the test.

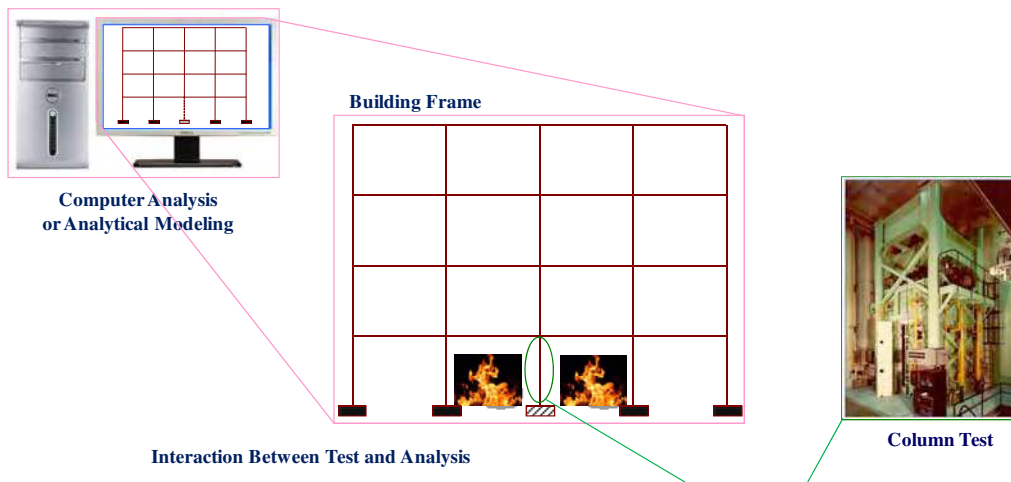


Figure 1 A hybrid testing technique for assessment of fire resistance of columns considering the restraint conditions from the structural system.

Figure 2 illustrates the test technique for testing of the right corner column of the first floor of a 3-bay, 3-storey frame. The main contribution from the frame in this method is the frame vertical stiffness in the direction of the test column's axial thermal expansion. When the test column is exposed to fire it elongates vertically due to

thermal expansion which results in vertical displacement of the column. A future enhancement of this method is to include the horizontal component of thermal expansion as an extra horizontal spring model on the column.

When the column is at the ambient temperature, typically it is only under the initial axial load P_o due to the gravity load. In order to include the effect of frame restraint, an additional deformation-dependent load ($k\Delta$) is added to the initial load P_o using Equation (1).

$$P = K\Delta + P_o \quad (1)$$

where Δ is the column axial deformation during the fire test; K is the vertical stiffness of the frame at the column's support and P_o is the initial applied axial load. The test can be implemented with either load or displacement control using Equation (1).

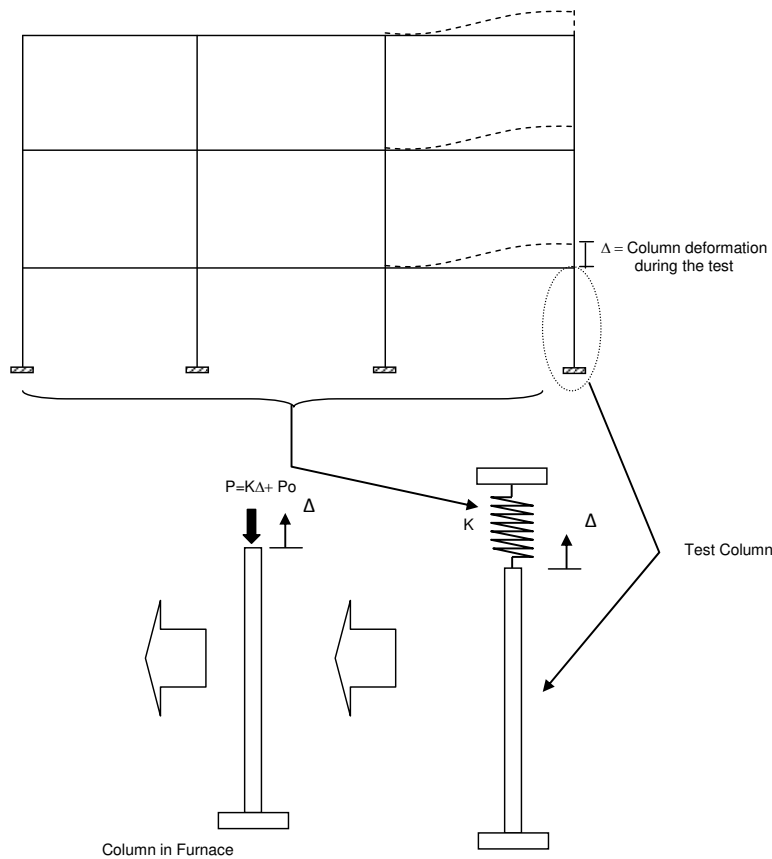


Figure 2. A simple performance based test technique for fire resistance of columns considering the restraint conditions from the structural system.

INTERACTION COMPONENTS

Figure 3 illustrates a three storey frame when it is detached from the test column. It shows the interaction components of load, P , and deformation, Δ , between the frame

and the test column and the vertical load-deformation, $P-\Delta$, relation. The $P-\Delta$ curve is the main result obtained from the analysis which will be employed later to control the load/deformation of the test column during the test.

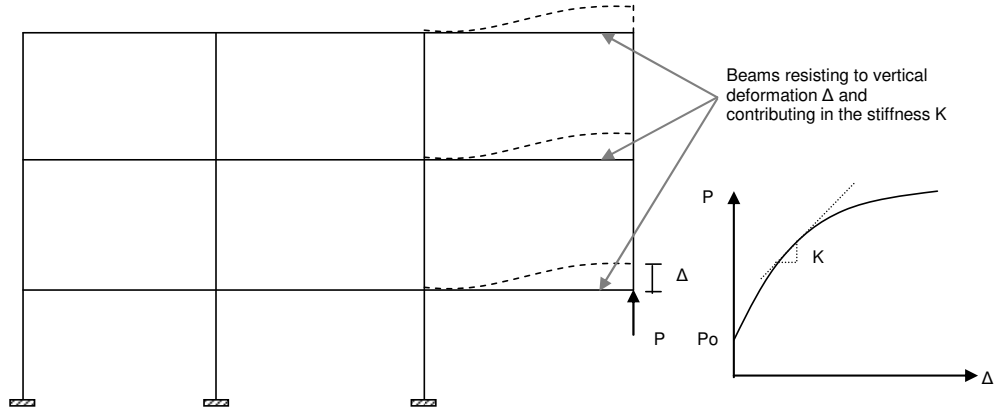


Figure 3. Load and deformation interaction components between the column specimen and the remainder of the structural system.

THE SIMPLIFIED METHOD

A Simplified Equation

An attempt was made to develop a simple analytical process to determine the structure vertical stiffness, K , implemented in hand calculation. In this method, K is determined according to Equation (2), derived for a beam with flexible supports.

$$K = \sum_{i=1}^n \left[\left(\frac{1-0.5\alpha}{1+\alpha} \right) \frac{12EI}{L^3} \right]_i \quad (2)$$

where n is the number of beams that are resisting against vertical movement of the test column. In Figure 3, three beams are resisting vertical movement and are accordingly deformed. Therefore, $n = 3$ for a corner test column, but in case of the middle test columns, in the same figure, $n = 6$; E , I , and L are respectively Modulus of Elasticity, Moment of Inertia, and Length of the beam; i is an index number identifying a particular beam; and α , the Beam Connections Rigidity Factor, which is between 0 and 1, which in turn is determined based on the rigidity ratio of beam connections, as described in the next section. Derivation of Eq. (2) and numerical examples were provided by Mostafaei and Hum (2009).

Beam Connections Rigidity Factor

The rigidity of the beam connections is included in Equation (2) using factor α . Figure 4 illustrates values of α for different beam support conditions.

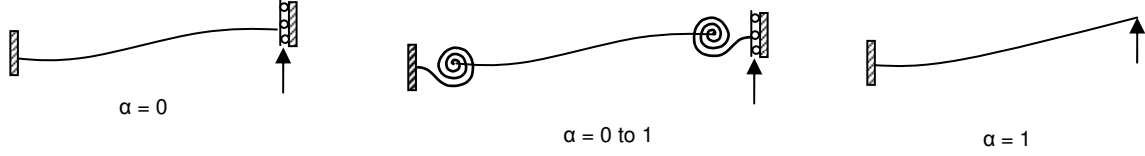


Figure 4. Factor α for fixed, variable and cantilever beams.

In general factor α could be determined by Equation (3).

$$\alpha = \frac{1}{1 + \frac{LK_a}{2EI}} + \frac{1}{1 + \frac{LK_b}{2EI}} \quad (3)$$

where E , I , and L are components of the beam i and K_a and K_b are the beam's end support rigidities to rotation determined by Equation (4).

$$K_a = \sum_{i=1}^{m_a-1} \left(\frac{\phi EI}{L} \right)_i \quad \text{and} \quad K_b = \sum_{i=1}^{m_b-1} \left(\frac{\phi EI}{L} \right)_i \quad (4)$$

where E , I , and L are determined for the beams and columns connected to beam i in Equation (2), except the beam i . m_a and m_b are total number of beams and columns connected to beam i at a and b respectively. Lateral Rigidity Factor, ϕ , of the beams and columns in Equation (4) is between 1 and 4 based on beam or column rigidity against lateral movement.

Lateral Rigidity Factor

For all beams, the lateral rigidity factor can be determined based on the axial rigidity of the columns in the frame, which is comparatively high for typical building structures. In low to moderate rise frames, a ϕ between 3.0 and 3.5 would be reasonable. This also applies to columns in a braced frame where lateral movements are limited by the bracing system. In this study, a value of $\phi = 3.5$ is considered for lateral rigidity of the beams. For columns in moment-resisting frames, ϕ is relatively more variable and determined according to Equation (5).

$$\phi = 4 - \left(\frac{3}{1 + \frac{K_S L^3}{12EI}} \right) \quad (5)$$

where E , I , and L are calculated for the column and:

$$K_s = \frac{1}{\sum_{i=1}^n \frac{1}{\sum_{j=1}^m \left(\frac{12EI}{L^3} \right)}} \quad (6)$$

where K_s is the lateral rigidity for column s ; E , I , and L are components for column j in floor i ; n is number of floors in and underneath of column s and m is number of columns in floor i .

For simplicity, one may consider all the columns to be similar in equations (5) and (6), resulting in:

$$\phi = 4 - \left(\frac{3}{1 + \frac{m}{n}} \right) \quad (7)$$

For the test column in Figure 2, $n = 1$ and $m = 4$, therefore, $\phi = 3.4$.

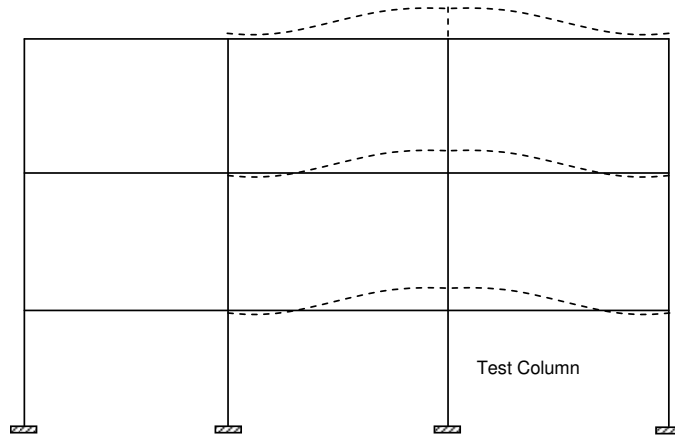


Figure 5. Roughly symmetric deformation and rotation in connections in frames when a middle column is selected for the test.

Equation (6) applies when all connections are rigid for rotation. In the case of a middle test column where there is more likelihood of symmetric frame deformations, as shown in Figure 6, this equation may be applicable. However, for a corner test column, due to asymmetric deformations (see Figure 6), connections are also rotating according to the beam's stiffness. Based on the analysis implemented for different frames in this study, when a corner column is selected as the test column, ϕ is considered as 55% of the values determined by Equation (5). This value may be reduced for frames with higher number of floors, but for the group of frames in this study such a value seems reasonable. Further study is needed on this.

FULL ANALYSIS FOR MODEL VERIFICATION

For model verification, the entire structure frame was simulated using a structural analysis program. In this study, the SAFIR computer program, developed at the University of Liege for the simulation of the behavior of building structures subjected to fire (Franssen, 2007), was used for the analysis.

As an example, the full analysis method was applied using the SAFIR program for a three storey frame, frame U1, with material properties provided in Table 1 and Table 2. The results are illustrated in Figure 6. The P- Δ curve was obtained by simulating the entire frame and exposing only the test column to the ASTM E119 temperature-time curve.

Although the P- Δ curve is nonlinear at the large deformations, in most cases, the axial deformation of the test column would not exceed the linear part of the P- Δ curve. Therefore stiffness K may be considered constant for the duration of the test. This provides more stability and makes the load control process of the test easier. If the axial deformation exceeds the linear stage of the curve then the nonlinear relation for K is used.

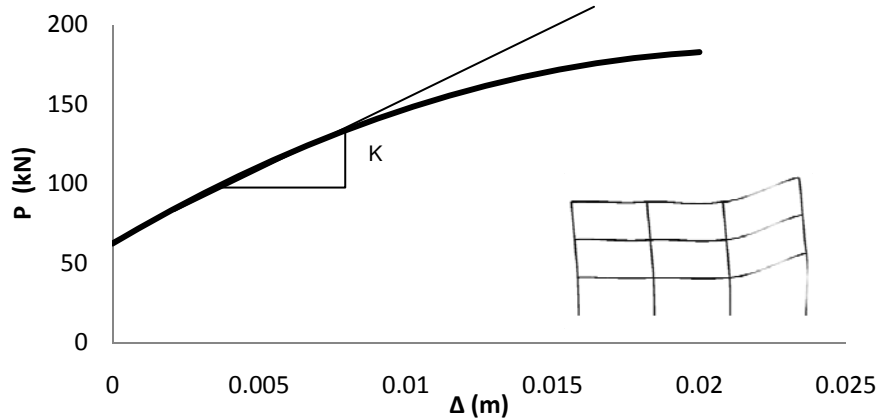


Figure 6. P- Δ curve obtained by implementing a full analysis using the SAFI software.

MODEL VERIFICATION

Six steel frame prototypes with different heights have been selected for this study: model verification for reinforced concrete frames were provided by Mostafaei and Mannarino (2009). The analysis was implemented for both corner and middle test column cases. Beam and column details are provided in Table 1 and Table 2. Dimensions of the frames are provided in figures 7(a) to 7(f). The frame sections and dimensions were selected according to typical steel building frames seen in the North America.

Both the full analysis method using the SAFIR program and the simplified method were implemented to determine the vertical frame stiffness corresponding to test columns of the frame prototypes. Some of the results were illustrated and compared in figures 8 to 13, for the full result see report by Mostafaei and Hum (2009). The comparison and correlation between the results of the two approaches indicate that the simplified method provides relatively acceptable values for the frame equivalent vertical load, P , deformation, Δ , and stiffness K .

Table 1. Details of frame prototypes.

Frame	No. of Stories	Test Column	Column Serial Size (mm)	Column Length (mm)	Beam Serial Size (mm)	Beam Length (mm)
U1a	3	1 st floor, corner	W360x370 (147.3)	3800	W610x180 (81.9)	7000
U1b	3	1 st floor, middle	W360x370 (147.3)	3800	W610x180 (81.9)	7000
U1c	3	2 nd floor, middle	W360x370 (147.3)	3800	W610x180 (81.9)	7000
U2a	6	1 st floor, corner	W360x370 (196.4)	3800	W610x230 (113.1)	7000
U2b	6	1 st floor, middle	W360x370 (196.4)	3800	W610x230 (113.1)	7000
U2c	6	2 nd floor, middle	W360x370 (196.4)	3800	W610x230 (113.1)	7000
U2d	6	5 th floor, middle	W360x370 (196.4)	3800	W610x230 (113.1)	7000
U3a	10	1 st floor, corner	W360x410 (236.6)	3800	W760x265 (147.3)	7000
U3b	10	1 st floor, middle	W360x410 (236.6)	3800	W760x265 (147.3)	7000
U3c	10	2 nd floor, middle	W360x410 (236.6)	3800	W760x265 (147.3)	7000
U3d	10	5 th floor, middle	W360x410 (236.6)	3800	W760x265 (147.3)	7000
U3e	10	8 th floor, middle	W360x410 (236.6)	3800	W760x265 (147.3)	7000
U4a	3	1 st floor, corner	W360x370 (147.3)	3800	W610x180 (81.9)	7000
U4b	3	1 st floor, middle	W360x370 (147.3)	3800	W610x180 (81.9)	7000
U4c	3	2 nd floor, middle	W360x370 (147.3)	3800	W610x180 (81.9)	7000
U5a	6	1 st floor, corner	W360x370 (196.4)	3800	W610x230 (113.1)	7000
U5b	6	1 st floor, middle	W360x370 (196.4)	3800	W610x230 (113.1)	7000
U5c	6	2 nd floor, middle	W360x370 (196.4)	3800	W610x230 (113.1)	7000
U5d	6	5 th floor, middle	W360x370 (196.4)	3800	W610x230 (113.1)	7000
U6a	10	1 st floor, corner	W360x410 (236.6)	3800	W760x265 (147.3)	7000
U6b	10	1 st floor, middle	W360x410 (236.6)	3800	W760x265 (147.3)	7000
U6c	10	2 nd floor, middle	W360x410 (236.6)	3800	W760x265 (147.3)	7000
U6d	10	5 th floor, middle	W360x410 (236.6)	3800	W760x265 (147.3)	7000
U6e	10	8 th floor, middle	W360x410 (236.6)	3800	W760x265 (147.3)	7000

W = Distributed load on beams, W (all beams) = 30000 N/m
E (steel)= 2.0×10^{11} N/m² fy (Steel)= 2.9×10^8 N/m²

Table 2. Details of Steel.

Serial Size	Mass Per Unit Length	Area	Depth	Width	Web Thickness	Flange Thickness	Corner Radius
(mm)	(kg/m)	(cm ²)	(mm)	(mm)	(mm)	(mm)	(mm)
W760x265	147.3	187.7	753.1	265.4	13.2	17.0	16.5
W610x230	113.1	144.5	607.6	228.3	11.2	17.3	12.7
W610x180	81.9	104.5	598.7	177.9	10.0	12.8	12.7
W360x410	236.6	301.3	380.5	395.4	18.9	30.2	15.2
W360x370	196.4	250.3	372.4	374.0	16.4	26.2	15.2
W360x370	147.3	187.7	359.7	370.0	12.3	19.8	15.2

*Data copied from JFE Steel Corporation "W-Beams.pdf", Cat.No.D1E-101-01.

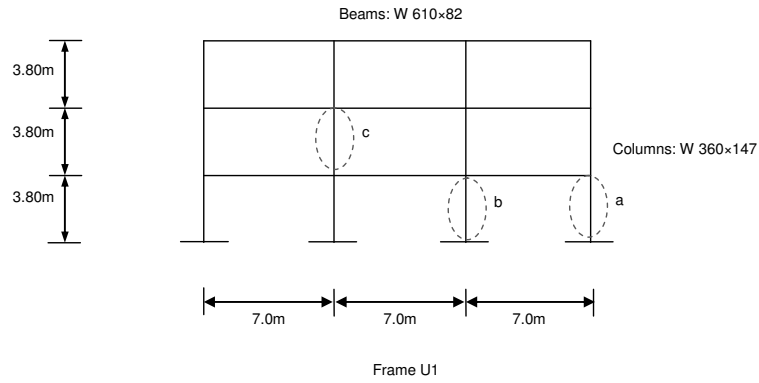


Figure 7(a). Details of columns and beams for frame U1.

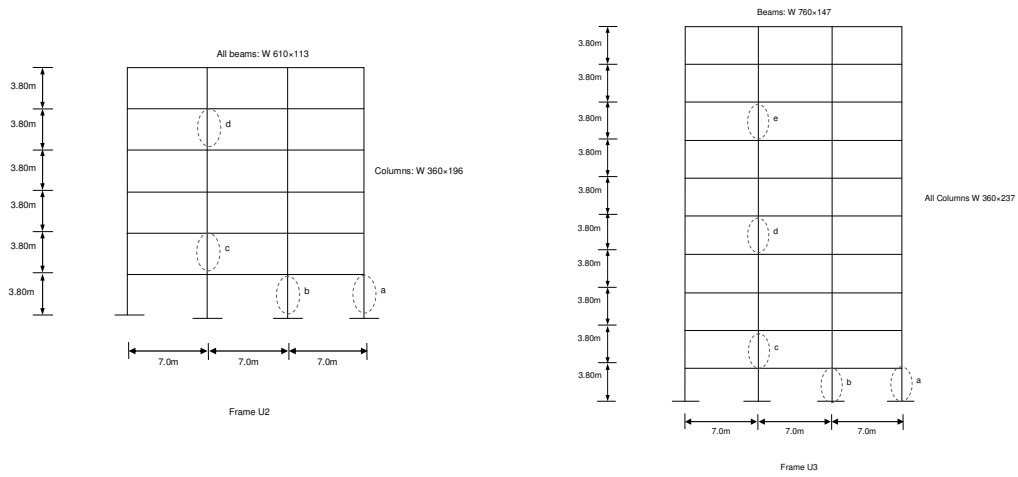


Figure 7(b). Details of columns and beams for frame U2

Figure 7(c). Details of columns and beams for frame U3

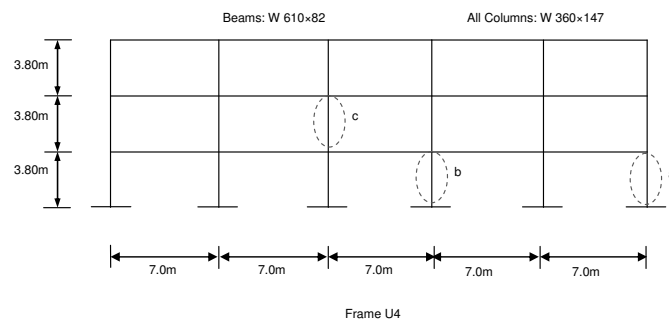


Figure 7(d). Details of columns and beams for frame U4.

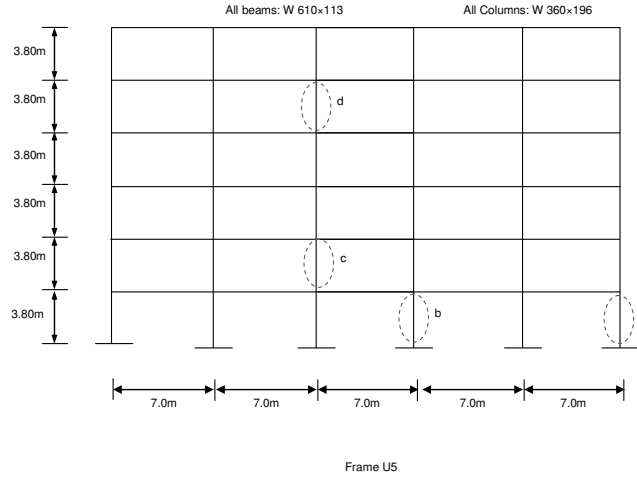


Figure 7(e). Details of columns and beams for frame U5.

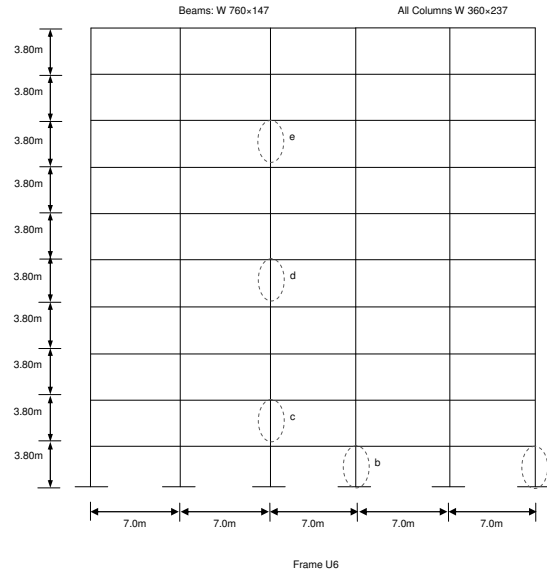


Figure 7(f). Details of columns and beams for frame U6.

CONCLUSIONS

A new hybrid test technique could be implemented to assess fire performance of building columns. The calculation process, developed in this study, is a simple method for determining the effect of the vertical structural frame response on fire resistance of the columns. Load and deformation of the test column, at the support, were examined to be the main interaction components between the analytical model and the test specimen. The method was implemented and verified for columns in different stories in six different steel building frames. Studies are still being carried out to implement the approach to include consideration of the lateral load due to floor thermal expansion.

ACKNOWLEDGEMENT

Acknowledgements are extended to Jessica Mannarino and Joe K. Hum, for their contributions in this study.

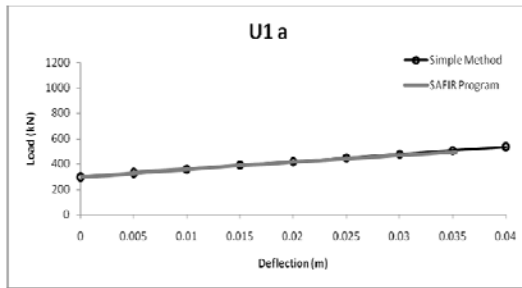


Figure 8. Load-Deformation (P-Δ) curve for prototype U1a.

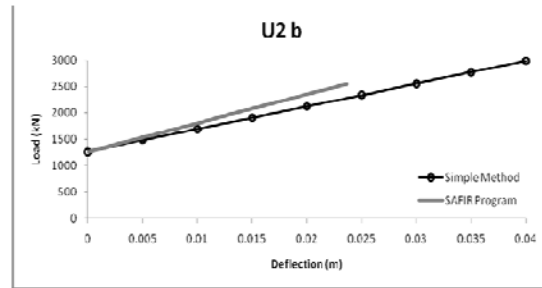


Figure 9. Load-Deformation (P-Δ) curve for prototype U2b.

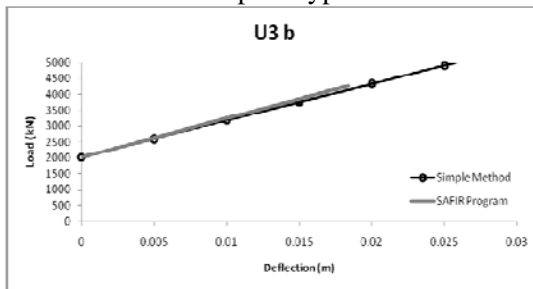


Figure 10. Load-Deformation (P-Δ) curve for prototype U3b.

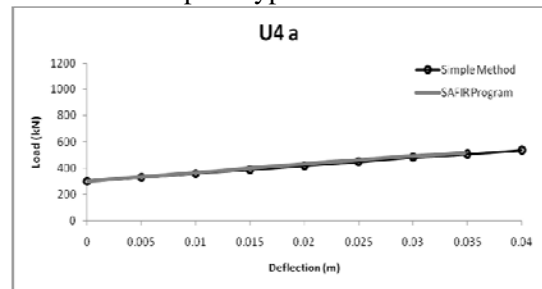


Figure 11. Load-Deformation (P-Δ) curve for prototype U4a.

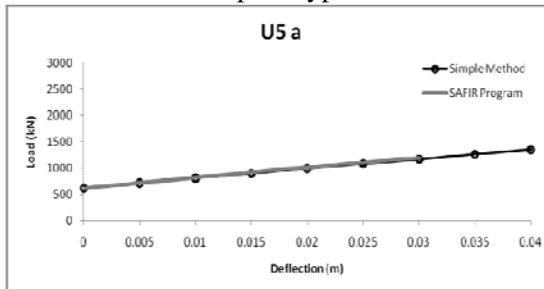


Figure 12. Load-Deformation (P-Δ) curve for prototype U5a.

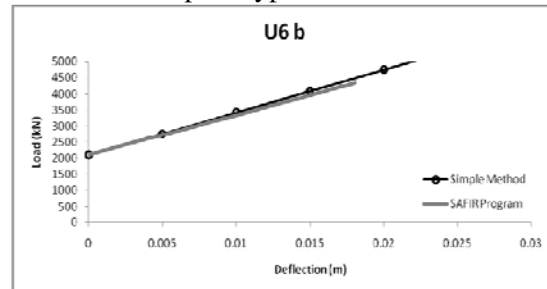


Figure 13. Load-Deformation (P-Δ) curve for prototype U6b.

REFERENCES

- Franssen, J.M. (2007). "User's Manual For SAFIR 2007a Computer Program For Analysis of Structures Subjected to Fire." *University of Liege, Belgium*.
- Mostafaei, H., Mannarino, J. (2009). "A Performance-based Approach for Fire-Resistance Test of Reinforced Concrete Columns." *National Research Council Canada, Research Report, No. 287*.
- Mostafaei, H., Hum, J.K. (2009). "A Hybrid Fire-Resistance Test Method for Steel Columns." *National Research Council Canada, Research Report, No. 292*.