MULTI-HAZARD ANALYSIS BY HYBRID SIMULATION OF BUILDINGS IN FIRE AND FIRE FOLLOWING EARTHQUAKE

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Abstract

In this research, the hybrid simulation technique originally developed for earthquake engineering applications is discussed and further developed for structures exposed to fire hazard. The performance and risks of large-scale structures subjected to system-level fire load effects by the new hybrid simulation technique, referred to as hybrid fire simulation or fire following earthquake (FFE) hybrid simulation. This innovative testing technique combines the advantages of the efficiency in numerical modelling and the accuracy in physical testing. It is a reliable and economical approach to assess the performance of the complete structural systems exposed to fire and fire following earthquake. Full interaction effects between the thermal and mechanical behaviour of the structures are considered in the assessment using the proposed methodology. In the proposed multi-hazard hybrid simulation framework, the element of the prototype structure that is exposed to the sequence of fire loads is selected as physical domain for physical test while the remainder structure as numerical domain is simulated by numerical models. In the physical domain of a fire following earthquake hybrid simulation, the test structure is first subjected to the strong earthquake ground motions. Then, using novel hybrid fire simulation techniques, the structure is subjected to the temporal and spatial distribution of sequential fire loads. Heat transfer and thermomechanical analysis is carried out as the fire starts, during which the thermal and mechanical information of the numerical domain are transferred to the physical specimen and the measured response at the same degrees-of-freedom of the physical domain are sent back to the numerical analysis. New OpenFresco objects for beams/columns are developed to include both temperature and mechanical degrees-of-freedom with full compatibility on deformation as well as the thermal flux and force equilibrium at the interface between the physical and numerical domains. A numerical simulation example of a building subjected to the multi-hazard scenario of fire following earthquake is presented to gain insight into the post-earthquake fire effect on structures.

Keywords: hybrid simulation, multi-hazard, fire following earthquake, performance-based design

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1. Introduction

Current design procedure does not consider the compound effects of concurrency or sequence of multiple hazards, e.g. fire following earthquake, blast following earthquake or fire and tsunami following earthquake. Although the probabilities of occurrence of such multi-hazard events have a wide range from low to level of concern, the consequence nevertheless can be devastating. Past multi-hazard events of fire following earthquake had been reported to have inflicted heavy casualties and economic losses during the San Francisco earthquake in 1906, Northridge earthquake in 1994 and Kobe earthquake Japan in 1995. As part of the effect in advancing performance-based design of structures, it is necessary to develop new design methodologies for structures against multi-hazard events to enhance the resilience and performance of next generation structures in the future.

The current structural design practice in dealing with the effects and actions for fire is the prescriptive method, which is to design structures following the code provisions to ensure the structural elements remain structurally functional within a certain period of time when exposed to fire, without considering the interactions with other structural members. The understanding of the prescriptive approach is based on standard fire tests, in which a single structural component or assemblage with idealized boundary conditions is subjected to elevated temperature represented by standard fire curves e.g. CAN/ULC-S101, ASTM E119, or ISO 834 [1-3]. Although the prescriptive code-based design is convenient and standardized, it does not take into account the global structural behaviour e.g. redistribution of loads, the deterioration of stiffness and increase of deformation as an entire structural system. To address these limitations, the new design method available in fire safety engineering which can assess the complete structural performance is the performance-based design approach. Recently, there has been studies on performance-based design of fire or fire following earthquake [4].

To assess the global structural performance, numerical modelling method can be adopted; however, the challenge in modelling increases in dealing with the complicated temperature dependent material properties, nonlinear behaviour in structures and complex structural configurations. As a result of these issues, it is more realistic to carry out fire tests. A reliable measure to obtain the entire structural behaviour exposed to fire or fire following earthquake is to carry out full-scale fire tests, yet only a few cases have been conducted as pilot studies since they are prohibitively expensive and impractical as a routine testing method.

In light of the need for improving the design of structures against fire or fire following earthquake discussed above, it is necessary to develop a more efficient, accurate and cost-effective testing technique alternative to full-scale fire tests to the better understanding on the performance of the complete structural systems under fire and fire following earthquake. For this purpose, a new fire testing approach referred to as hybrid fire simulation based on the recently developed methodology of hybrid simulation in earthquake engineering is proposed, which combines physical testing and numerical modelling. An overview of the methodology of hybrid fire simulation is presented as follows. First, the fire scenario and fire load are defined for the prototype structure; then the part of the structure directly exposed to fire load is selected as the testing specimen for testing in a furnace (physical domain), while the remainder structure is numerically simulated (numerical domain). The thermal and mechanical response is transferred between the two sub-domains through an interface platform in real-time. In the physical test domain of hybrid fire simulation, in addition to the fire effects, i.e. the temporal and spatial distribution of the fire loads, the test specimen is also subjected to the gravity and lateral loads from the rest of the structure as determined from the numerical domain of the structure. After the fire starts, in each time step, the measured force and temperature from the physical domain will be fed back to the numerical simulation through the interface, and the finite element software will start the thermomechanical analysis to calculate the structural response and send the thermal and mechanical information at the connection back to the physical specimen; and then move on to the next cycle until the end of the test.

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In the following, an overview of the previous research on hybrid fire simulation is presented. A new framework and the methodology of real-time multi-hazard scenario of post-earthquake fire hybrid simulation which includes full interaction effects for performance-based assessment of complex building structures are proposed.

2. Overview of Hybrid Fire Simulation

Hybrid fire simulation has started to attract increasing attentions in recent years. However, there have only been limited number of studies on combining physical testing and numerical modelling in fire research. Table 1 shows a summary of previous research. The first hybrid fire simulation can be found in literature was reported by Korzen et al in 1999 and 2002 [5,6], the proposed framework is shown in Fig. 1. In their studies, an 8-storey steel frame building was chosen as the demonstrating structure. One column was physically tested in the gas furnace at BAM (Federal Institute for Materials Research and Testing) in Germany and the rest of the structure was represented by a predefined idealized model of the rest of the structure as a constant axial stiffness. The axial displacements and forces at the interface were exchanged through a 6-channel control system in the laboratory. In 2010, Robert [7] at CERIB (Centre for Studies and Research of the Concrete Industry) in France conducted a hybrid fire simulation test of a single-storey concrete frame, the physical domain was a concrete slab with three degrees-of-freedom controlled in total (one axial elongation and two rotational at the supports); whereas the numerical domain was represented by an elastic stiffness matrix. Later in 2012, Mostafaei [8,9] successfully tested a column in a 6-storey reinforced concrete building in a gas furnace at NRC (National Research Council Canada) in Ottawa through hybrid fire simulation shown in Fig. 2. In his study, the numerical domain was simulated as a 2D/3D finite element model in a special purpose finite element software SAFIR [10]. The calculated axial deformations and forces at the interface of the numerical domain were exchanged with the physical domain in each time step. However, in this early hybrid fire simulation, the data transformation and exchange within the physical and numerical domains was not automated and required human interaction. The first fully computer-controlled hybrid fire simulation with a finite element model for the numerical domain was proposed by Whyte et al [11] in 2014, the framework is presented in Fig. 3. In their research, a new OpenFresco [12] truss element with one temperature degree-of-freedom at each end node was developed, which can be adopted to realize one-way or two-way coupling between the sub-domains of the structure. The small-scale proof of concept hybrid fire simulation of a 2D elastic truss structure was carried out at ETH (Swiss Federal Institute of Technology) within the OpenSees [13] and OpenFresco frameworks. A similar test was carried out by Schulthess et al [14] using ABAQUS [15] and an interface server instead. The most recently published research work on hybrid fire simulation was by Wang et al [16] at University of Toronto in 2018. In their proposed method as demonstrated in Fig. 4, fully automated and displacement control with proper error compensation scheme was realized and validated in a full-scale hybrid fire simulation through the UT-SIM interface platform [17].

It is noted, all the previous attempts on hybrid fire simulation discussed above typically do not consider the full interactions between the numerical and physical domains of the structure, because of insufficient number of mechanical and thermal degrees-of-freedom at the interface. Specifically, the mechanical degrees-of-freedom was limited to axial load in most previous studies. In terms of the consideration on the thermal effects at the interface e.g. heat conduction between the heated and adjacent structural elements, Whyte el al. [11] adopted their newly developed element to send temperatures to the physical specimen, and Wang et al. [16] applied a previously generated time-temperature history of physical specimen on the numerical domain at the interface node. However, these two approaches can be adopted when the structural members are not sensitive to the temperature distribution within the cross sections and the mechanical behaviour of the structure has no impact on the fire load.

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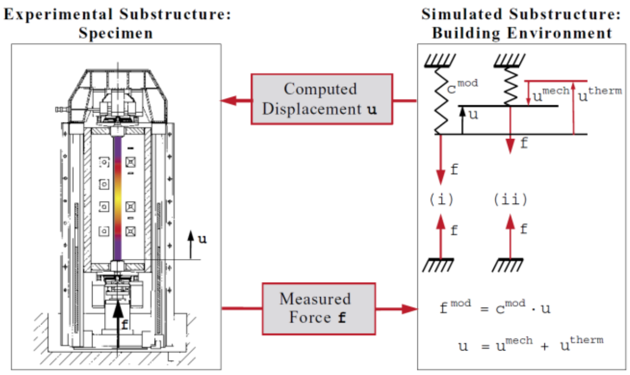

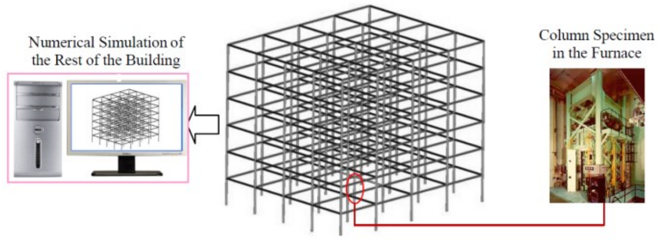

Fig. 1 - Hybrid fire simulation framework [6] Fig. 2 - Hybrid fire simulation for the 6-storey building [9]

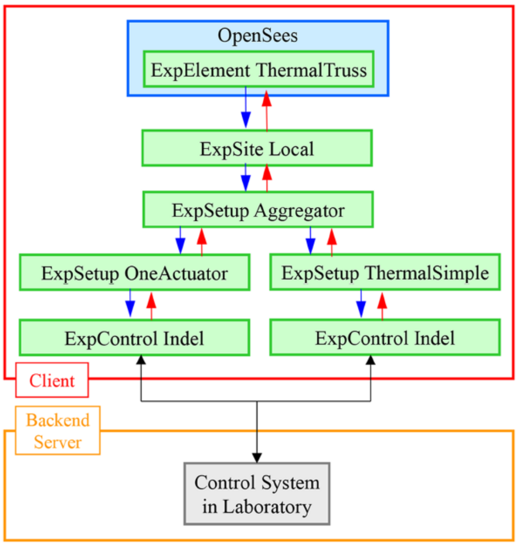

Fig. 3 - OpenFresco/OpenSees hybrid fire simulation architecture [11]

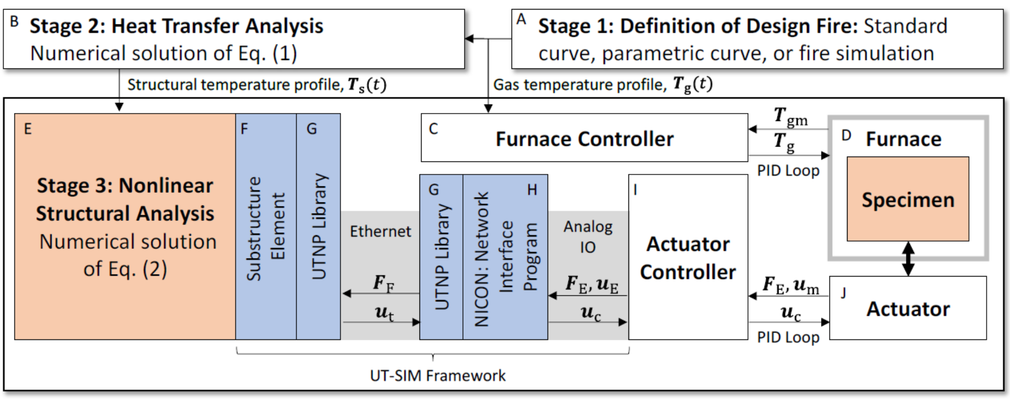

Fig. 4 - Stages of hybrid fire simulation through UT-SIM [16]

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Table 1 - Summary of previous research on hybrid fire simulation

Previous Research	Structure	Testing Facility	Physical Domain	Interface	MDOF	TDOF	Numerical Domain	Heat Conduct to Adjacent Components
Korzen et al. (1999)	8-storey steel frame	Gas Furnace (BAM)	Single column	6-channel control system	1 (axial)	--	Constant axial stiffness	--
Robert et al. (2010)	1-storey concrete frame	Gas Furnace (CERIB)	Single slab	--	3 in total (1axial+ 2rotational)	--	Constant stiffness	--
Mostafaei (2012)	6-storey reinforced concrete frame	Gas Furnace (NRC)	Single column	Human interaction	1 (axial)	--	SAFIR 2D/3D (nonlinear)	--
Whyte et al. (2014)	steel truss	Electric Furnace (ETH)	Single truss	OpenFresco/New objects for truss element	1 (axial)	1	OpenSees/Standard (linear)	--
Schulthess et al. (2016)	steel truss	Electric Furnace (ETH)	Single truss	Server	1 (axial)	--	ABAQUS (user subroutine)	--
Wang et al. (2018)	4-storey steel frame	Gas Furnace (KIST)	Single column	UT-SIM	1 (axial)	--	ABAQUS (nonlinear)	Predefined time-temperature curve

Note: MDOF and TDOF represents the mechanical and temperature degrees-of-freedom considered at the interface node respectively

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3.Framework for Hybrid Fire Simulation

In the proposed hybrid fire simulation method within the framework of performance-based design in fire safety engineering, a key requirement in capturing the complete structural behaviour is to account for the full interaction effects. The interactions between the two sub-domains i.e. physical and numerical, include the heat transferred from the fire to the structures, heat conduction as well as the forces, displacements, rotations induced by the elevated temperature. In addition, it is also necessary to update the mechanical boundary conditions in both the numerical and physical domains in real-time throughout the hybrid fire simulation to ensure full compatibility at the interface. The full interaction effects can be realized by coupling of the thermal analysis, mechanical analysis with thermal loading, high-performance testing facilities, and sufficient data exchange in the interface platforms. The details of a hybrid fire simulation protocol are presented.

3.1 Thermal Analysis

The thermal analysis aims at solving for the temperature profile in the structures exposed to fire, including (1) the convective and radiative heat transfer analysis from the fire to the surface of the structures by computational fluid dynamic (CFD) software; and (2) the conductive heat transfer within and among the structural elements using finite element analysis (FEA). In the proposed new framework, a one-way coupled analysis approach between CFD and FEA is adopted [18].

In the performance-based analysis, fire scenarios are chosen according to a number of factors e.g. the fuel type, the fuel consumption, the ventilation condition etc., which can be either represented by parametric fire curves or simulated by CFD software e.g. FDS (Fire Dynamic Simulator) [19] developed by NIST. Recognizing the complicity of the fire dynamic phenomenon in the convective and radiative heat transfer from the fire to the surface of the structures, it is more accurate to use the fire load curves generated by CFD simulation. Here as an assumption that the structural responses do not affect the fire load, e.g. no total collapse occurred during the analysis, a one-way coupled analysis between CFD and FEA can be used. After obtaining the temperature/heat flux profile at the surface of the structural elements by CFD, the conductive heat transfer is carried out to solve for the temperature gradient in the sections of the structural members using finite element (FE) software, e.g. SAFIR, OpenSees for Fire [20], ABAQUS etc.

3.2 Mechanical Analysis with Thermal Loading

In the mechanical analysis with thermal loading, typically by using specialized FE software packages specially developed for fire engineering, the structural responses under the static and thermally induced mechanical loading are calculated. The mechanical analysis is carried out sequentially after the thermal analysis based on the previously generated temperature profile in the structure. In the mechanical structural analysis within the proposed framework, the structure is subjected to the constant gravity load as well as the time variant forces, moments and the temperature gradient introduced from the physical domain at the interface node. The responses of the structure are calculated in the thermal-mechanical analysis are fed back to the physical specimen for the next cycle of hybrid fire simulation of the structure.

3.3 Testing Facilities

The National Research Council Canada (NRC) has conducted extensive fundamental research and innovative investigation on structural behaviour in fire. The NRC fire laboratory has a number of unique high-performance furnaces including a column furnace, a wall furnace and a floor furnace, which can carry out large-scale fire tests. The high-performance column furnace at NRC has the unique capability of conducting

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high temperature fire tests of full-scale specimens under controlled axial, lateral and rotational degrees-of-freedom and applied force and moment loading. It is one of the best large-scale furnaces in the world that can carry out hybrid fire simulation with full thermal and mechanical interaction effects.

3.4 Interface Platforms

To include the full interactions for performance-based design as mentioned before, it is necessary to have the capability for full information exchange and communication between the numerical and physical domains during the hybrid fire simulation. The implementation in the proposed framework is through the OpenFresco interface platform, which provide standard data exchange protocols. However, OpenFresco is originally developed for conducting seismic hybrid simulation for earthquake analysis, which only requires force and displacement information exchange between the numerical and physical domains. In order to conduct hybrid fire simulation, new thermal objects with the capability of exchanging nodal temperature information are developed as shown in Fig. 5.

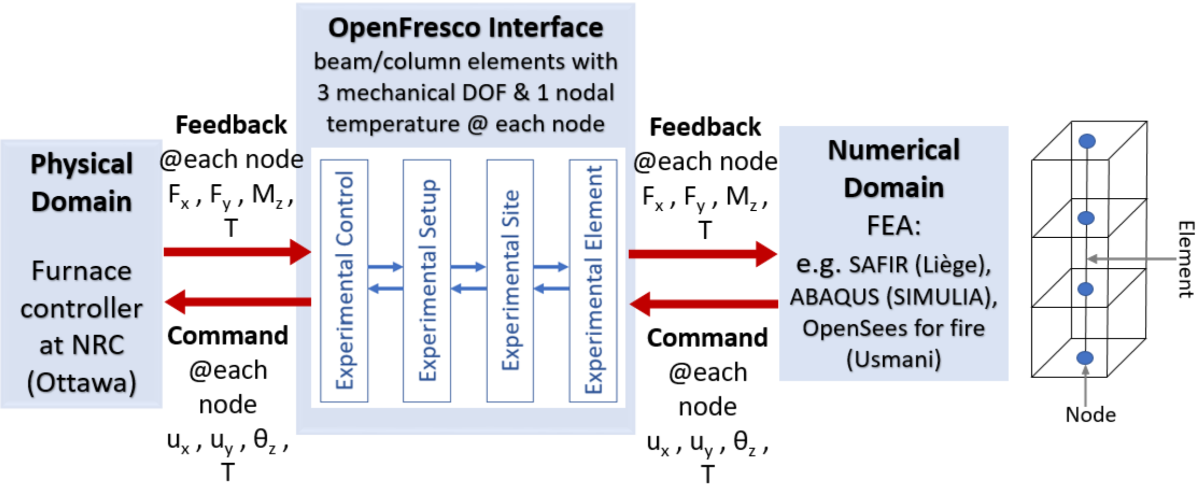

Fig. 5 - OpenFresco framework for hybrid fire simulation

3.5 Process of Hybrid Fire Simulation

The procedures of carrying out hybrid fire simulation, as shown in Fig. 6, are described as follows:

Step 1: define the fire scenario and obtain the fire load for the entire structure as shown in Fig. 6(a), by carrying out fire simulation in CFD software;

Step 2: conduct the thermal analysis with gravity load for the complete structure at ambient temperature to determine the initial mechanical boundary conditions i.e. axial and lateral displacements, moments, for the numerical and physical domains at the interface, as demonstrated in Fig. 6(b);

Step 3: impose the previously calculated initial loads on both the numerically modelled structure and the test specimen in the fire test furnace;

Step 4: initiate the fire load to the test specimen in the furnace as shown in Fig. 6(c);

Step 5: measure the thermal and mechanical responses at the interface node between the numerical and physical parts of the test structure at the end of the time step;

Step 6: apply the obtained nodal temperature gradient and the mechanical loads (transferred through the interface platform) on the numerical structure at the same degree-of-freedom, then sequentially carrying out the thermomechanical analysis to calculate the structural response;

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Step 7: impose the obtained structural response of axial, lateral displacements and rotations at the interface node from previous step of the physical specimen;

Step 8: repeat Step 5 to Step 7 until the end of the temperature-time history, or the cooling process.

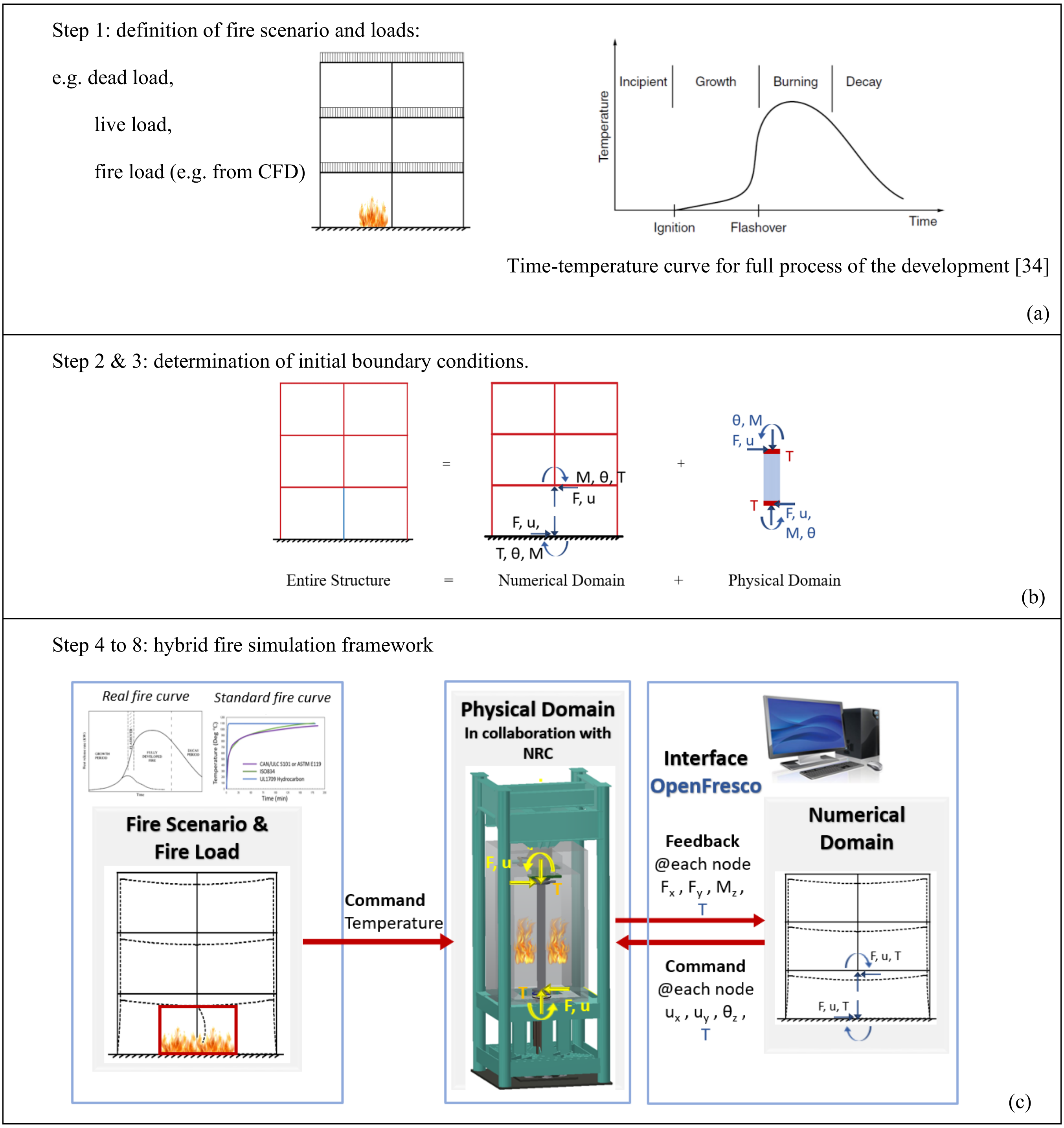

Fig. 6 - (a) Example of fire load and fire scenario (b) demonstration of initial boundary conditions (c) process of hybrid fire simulation from step 4 to step 8

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4.Framework for Fire Following Earthquake Hybrid Simulation

The proposed hybrid fire simulation method can be extended to evaluate full-scale system-level structural response of existing buildings or new constructions in fire following earthquakes. This allows the evaluation of the effect of earthquake damage to active and passive fire protection systems. In the novel multi-hazard hybrid simulation framework, the regular hybrid simulation for earthquake is carried out in the furnace, after which the earthquake damaged structure is exposed to fire using the proposed hybrid fire simulation technique. The most important stage is to account for the cumulative damage in the entire structural system under the earthquake and fire loading sequence. In the physical test domain, the seismic damage in the test specimen can be obtained directly after the hybrid simulation for earthquake. However, in the numerical domain of the structures, the earthquake damage state in the model need to be specially saved as the initial condition in the sequential analyses of structure in fire. There are some research works focus on enabling this kind of modelling capability between some finite element software e.g. between OpenSees and OpenSees for Fire [21], OpenSees and SAFIR [22].

5.Numerical Study on the Performance of a Steel Building Subjected to Fire Following Earthquake

To obtain insight into the effects of fire following earthquakes on structures, a numerical study on a 4-storey steel moment resisting frame with reduced beam section (RBS) connections subjected to fire following earthquake was carried out using 2D line model with gravity columns on the right side of the frame through finite element software ABAQUS. The earthquake simulation is conducted using nonlinear time history analysis where the frames are subjected to a far-field ground motion. With the damaged state of the structure at the end of the earthquake used as the initial condition for the fire analysis, an uncoupled thermal-mechanical analysis is performed with specified time-temperature curves applied on the heated elements exposed to fire. The results of the simulations can be used to reflect on the behavior of steel moment resisting frames under the combined loading conditions of earthquake and fire.

5.1 Prototype Steel Structure

The prototype 4-storey steel building with perimeter steel moment resisting frames using reduced beam section connections and interior gravity systems is designed based on FEMA-350 [23] stipulations by Jin and El-Tawil [24]. Fig. 7 shows the configuration of the frame, dimensions and cross sections of the beams and columns. In the design of RBS, a is taken as 75% as b_f, where b_f is the width of the beam flange; b equals to 85% of d_b, where d_b is the depth of the beam; and c equals to 20% of b_f.

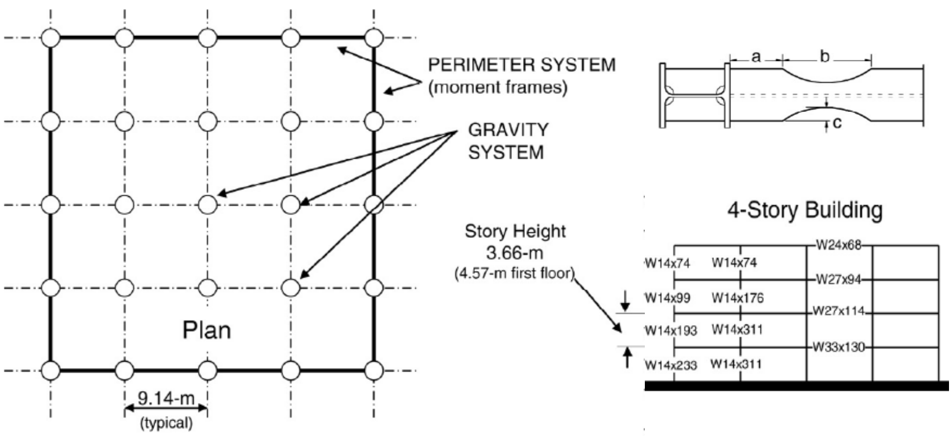

Fig. 7 - Design details of the prototype structure [24]

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5.2 Fire Following Earthquake Hazard Scenarios

The Kobe earthquake record is selected and scaled to the maximum considered earthquake level in accordance with FEMA-P695 [25].

The post-earthquake fire scenarios are shown in Fig. 8. To assess the performance of the steel building under realistic fire scenarios which includes both heating and cooling phases of the fire load, a parametric fire curve is selected as a representative fire load effect as shown in Fig. 9. The temperatures applied to the heated columns calculated according to Eurocode are also presented in Fig. 9.

Fig. 8 - Three considered fire hazard scenarios on the first storey of the building (a) fire located in the two left bays (b) fire located in the two middle bays and (c) fire located in the two right bays

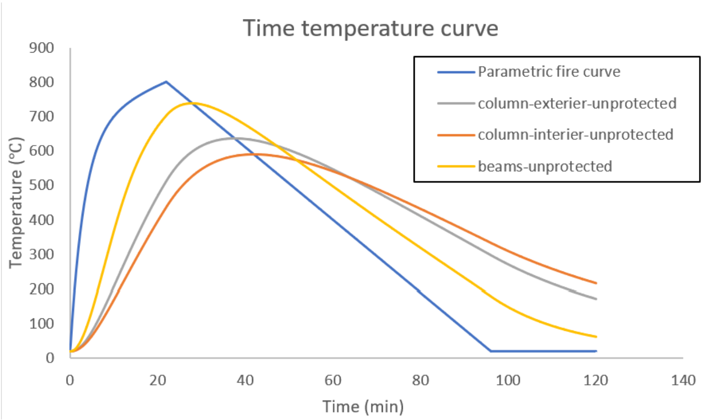

Fig. 9 – Time-temperature curve for parametric fire and steel temperature in beams and columns

5.3 Results and Discussion

The maximum and residual interstorey drift ratios for the structure under earthquake and fire following earthquake hazards with the fire occurring in three different locations are shown in Fig. 10 and Fig. 11. It is observed that the interstorey drifts of the building subjected to post-earthquake fires are larger than the case when earthquake comes alone. The effect of fire following earthquake is more pronounced at the lower floors where they are close to the fire as compared to the upper floors.

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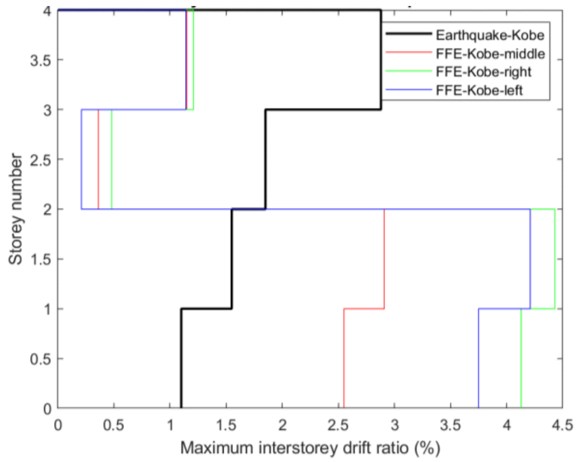

Fig. 10 - Maximum interstorey drift ratio

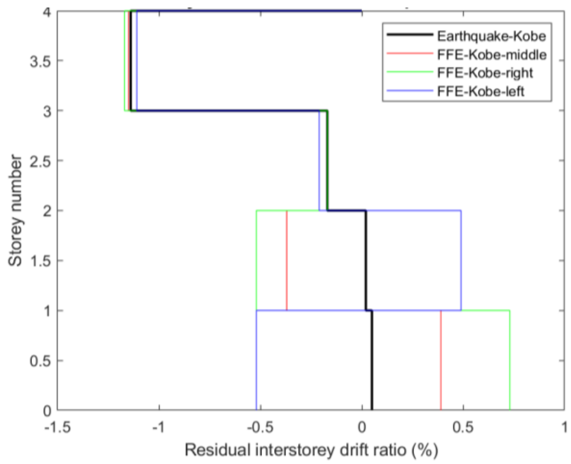

Fig. 11 - Residual interstorey drift ratio

6. Conclusions

The hybrid simulation framework for fire and fire following earthquake is an effective alternative approach to full-scale test. It is noted that both thermal and mechanical full information exchange at the interface between numerical and physical domains is important in capturing the behaviour and performance of complete structural systems, e.g. for considering fire spread scenarios.

In the fire following earthquake numerical simulation study, the results show that the sequential combination multi-hazard effect of fire following earthquake can introduce more damage to the example building when compared to the case of damage due to fire hazard alone. The risk of total collapse of the building is high in the post-earthquake fire hazard because of the large interstorey drifts of the lower floors. Therefore, it is necessary to develop design methods for structures against such multi-hazard events.

7. Acknowledgements

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8. References

[1] CAN/ULC. (2014). Canada/Underwriters' Laboratories of Canada. *Standard methods of fire endurance tests of building construction and materials*. CAN/ULC-S101. Prepared by ULC, Toronto, Canada.
[2] ASTM (2016). American Society for Testing and Materials. *Standard test methods for fire tests of building construction and materials*. ASTM E119-16a. Prepared by the ASTM, Reston, USA.
[3] ISO (2014). International Organization for Standardization. *Fire resistance tests-Elements of building construction-Part 11: Specific requirements for the assessment of fire protection to structural steel elements*. ISO 834-11:2014. By ISO, Geneva, Switzerland.
[4] Robertson J.N., Mehaffey J.R. (2000). "Accounting for fire following earthquakes in the development of performance based building codes". *The 12th world conference on earthquake engineering*, Auckland, New Zealand, 4 February 2000.
[5] Korzen M., Magonette G., Buchet Ph. (1999). "*Mechanical loading of columns in fire tests by means of the substructuring method*". Zeitschrift Fur Angewandte Mathematic Und Mechanik. Vol. 79, pp. 617-618.

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[6] Korzen M., Ziener K.U., Riemer S. (2002). "Some remarks on the substructuring method applied to fire resistance tests of columns". *World congress on housing*, Coimbra, Portugal, 9-13 September 2002.
[7] Robert F., Rimlinger S., Collignon C. (2010). "Structure fire resistance: a joint approach between modelling and full scale testing (substructuring system)". *The 3rd fib congress*. Washington DC, USA, 29 May-2 June 2010.
[8] Mostafaei H. (2013). "*Hybrid fire testing for assessing performance of structures in fire-methodology*". Fire Safety Journal, Vol. 58, pp. 170-179.
[9] Mostafaei H. (2013). "*Hybrid fire testing for assessing performance of structures in fire-application*". Fire Safety Journal, Vol. 56, pp. 30-38.
[10] Franssen J.M., Gernay T., (2017). "*Modeling structures in fire with SAFIR®: theoretical background and capabilities*". Journal of Structural Fire Engineering, Vol. 8 No. 3, pp. 300-323.
[11] Whyte C.A., Mackie K.R., Stojadinovic B. (2014). "Experimental modeling of the structural response to fire loads using the hybrid simulation technique". *10th U.S. national conference on earthquake engineering*, Anchorage, USA, 21-25 July 2014.
[12] OpenFresco. (2015). "Open framework for experimental setup and control". University of California, Berkeley.
[13] OpenSees. (2015). "Open system for earthquake engineering simulation". University of California, Berkeley.
[14] Schulthess P., Neuenschwander M., Fontana M., Knobloch M. (2016). "Consolidated fire testing: coupled thermo-mechanical modelling for analysis of the global structural fire behavior". 6th International conference on structural engineering, mechanics and computation, Cape Town, South Africa, 5-7 September 2016.
[15] SIMULIA Corp. *ABAQUS/Standard User's Manual, Version 6.13*. Providence, USA.
[16] Wang X., Kim R.E., Kwon O.S., Yeo I. (2018). "*Hybrid simulation method for a structure subjected to fire and its application to a steel frame*". Journal of Structural Engineering, ISSN 0733-9445.
[17] Kwon O.S., (2016). "UT-SIM [online]". Accessed 4 May 2018. https://www.ut-sim.ca/.
[18] Tondini N., Vassart O., Franssen J.M. (2012). "Development of an interface between CFD and FE software". *The7th international conference on structures in fire*, Zurich, Switzerland, 6-8 June 2012.
[19] McGrattan, K. B., McDermott, R. J., Weinschenk, C. G., and Forney, G. P. (2013). Fire Dynamics Simulator, Technical Reference Guide. NIST.
[20] Usmani A., Zhang J., Jiang J., Jiang Y., May I. (2012). "*Using OpenSees for structures in fire*". Journal of structural fire engineering, Vol. 3 No. 1, pp. 57-70.
[21] Khorasani N.E., Garlock M., Gardoni P., (2016). "*Probabilistic performance-based evaluation of a tall steel moment resisting frame under post-earthquake fires*", Journal of Structural Fire Engineering, Vol. 7 No. 3, pp. 193-216.
[22] Ni S., Birely C., (2018). "*Simulation procedure for the post-fire seismic analysis of reinforced concrete structural walls*". Fire Safety Journal. Vol. 95, pp. 101-112.
[23] FEMA 350. (2000). "*Recommended seismic design criteria for new steel moment-frame buildings*." Federal Emergency Management Agency, Washington, DC.
[24] Jin J., El-Tawil S. (2004). "*Seismic performance of steel frames with reduced beam section connections*". Journal of Constructional Steel Research. Vol. 61, pp. 453-471.
[25] FEMA P695. (2009). "*Quantification of building seismic performance factors*." Federal Emergency Management Agency, Washington, DC.

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