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Project Title	:	**Collapse analysis of Plasco tower using OpenSEES**
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Project outline

The aim of this project is to model and carry out collapse analysis of Plasco tower using the Open System for Earthquake Engineering Simulation (OpenSEES) which is a software framework for simulating the seismic response of structural and geotechnical systems.

The Plasco building which collapsed two years ago in Tehran, Iran was never designed to withstand fire. Unlike WTC towers, only limited structural drawings are available and most of the information obtained was by post collapse inspection. Because of these reasons, since its collapse, there hasn't been much research focused on what exactly caused the collapse. In case of Plasco tower the occupancy changes over several decades proved to be catastrophic during the fire. As there isn't much information available about how fire spread and its fuel load, determining this appropriate fire load scenario has become an important objective in this project.

Most commercial FEA software provide heat transfer analysis and simulate structural response accurately for simple fire scenarios. It is however extremely tedious to simulate the structural response to realistic complex fire scenarios (such as the so-called travelling fire) with the currently used software tools without expending lot of time and effort. Considering this it has also been a research interest to couple heat transfer analysis in OpenFOAM with thermo-mechanical analysis in the OpenSEES and thereby transferring nodal/elemental temperature histories from one model to the other. The structural model is said to be complete and reasonably accurate when this automation is achieved.

The past research on thermomechanical analysis was based on simplistic assumptions which become increasingly invalid as the size and complexity of a structure increases. The fire resistance of such large and complex structures must be more explicitly determined using performance evaluation approaches involving simulation of structural system response to realistic fire scenarios.

Because of its size and complexity in fire spread, the project of Plasco tower collapse analysis is of high research interest.

Plasco tower and the fire accident

The Plasco Tower, a steel frame high-rise building containing 15 stories above ground and two stories below ground was built in 1962. At the time of its construction, it was the tallest building in Tehran, the capital city of Iran. The building was occupied primarily by garment businesses. Large amount of fabrics was stored on the premises. On 19th January 2017, a fire accident occurred on the 10th floor and spread to other parts of the building which eventually resulted in the collapse of the building within four hours as shown in Fig. 1. It was believed that the fire was initiated by a short circuit in the electrical system. The accident resulted in loss of many lives including residents and fire fighters. In addition, hundreds of businesses were destroyed, and thousands of workers lost their employment.

(a) (b) (c)

Figure 1: Plasco Tower at different stages of the event (a) before the accident (b) during fire accident (c) at collapse (all images courtesy of IRNA NEWS Agency)

The building had two separate structural blocks; the 17-storey main tower standing beside a 5-storey building. The 17-storey building was 30m × 30m in plan with two floors below the ground level and fifteen floors above the ground level. The height of the ground floor was 6.3m compared to 3.8m for other floors. The 5-storey building was a 105m long shopping mall along the North-South direction and had 3200 m2 floor area approximately. Weaker section columns were placed along the periphery to resist the lateral loads such as wind and earthquake loads. Whereas stocky columns were placed in the centre to safely transfer the gravity loads to the foundation. Altogether, there were 50 columns in the building. The corner columns and two perimeter columns at the centre of each face were double the size of the other thinner 34 perimeter columns. The double-sized perimeter columns near the middle of each face were aligned with the four stocky interior core columns. The perimeter columns on the south side were not connected to the foundation in order to provide free access to the adjoining 5-story part of the structure. Due to the lack of structural drawings and other information during the fire incident, many field inspections were conducted to establish the details of all structural members. All the structural members were welded built-up sections, meaning that they were made by welding multiple steel profiles such as U and L-shaped profiles. The flooring system comprised of a concrete slab with a thickness of 120 mm, which was supported by a series of ceiling trusses in both perpendicular directions forming a dense steel grillage structure. The structure details have been discussed in depth by Behnam [1].

It was reported by TFSD that the fire started at north-west corner on the 10th story of the building. By analysing the photographs in detail, fire was assumed to have travelled along the floor horizontally and across the floors through staircase and windows vertically.

OpenSEES for fire

OpenSEES is an open source software which was originally developed for simulating the seismic response of structural and geotechnical systems. It was originally developed at the University of California, Berkeley [2] to analyze structures under seismic loading, and was later extended to perform structural fire analysis by research group of Usmani at the University of Edinburgh [3–4], and Brunel University London [8, 9] UK. Currently, the development of thermal OpenSEES is being carried out by fire research group at Hong Kong Polytechnic University [10].

OpenSEES is an object-oriented software implemented in the C++ language, through an open-source development process and uses the 'Tcl' scripting language as the platform. As models in

OpenSEES are created using Tcl language it lacks a user-friendly visual interface. To model a complex structure using Tcl script such as Plasco Tower is an exhaustive task and may lead to many errors in the code. To overcome this problem a GiD pre-processor has been coupled with OpenSEES. Using the OpenSEES GiD interface, the deformed shape of the model and deflection response of a typical floor can be seen. Moreover, only top ten floors are modelled to reduce the computational cost.

All the members in the structure were modelled using displacement-based beam column elements available in the OpenSEES library (dispBeamColumnThermal) and ShellMITC4Thermal. The fiber section approach is followed while modelling of sections where each Fiber Section object is composed of multiple fibers and a uniaxial thermal material is assigned to all the fibres. The fiberSecThermal object class enables the user to apply thermal load at 2, 5 or 9 points across the depth of the section. Since the thickness of sections used in the Plasco Tower was small, no temperature variation across the depth of sections is assumed as of now; in other words, the temperature gradient across the section is assumed to be zero.

Project Progress

The structural modelling of the Plasco tower began without considering the slab i.e., slab is assumed as a dead load simply resting on underneath frame system. In our investigation of the Plasco Tower structural system we could not find a definitive answer to the question about whether the concrete floor slab was composite with the supporting grillage or simply rested on top of it. Even if it has composite action it cannot be acertained to what extent. Hence the work on this project started by acknowledging this fact. A grillaage model has been made which structurally represents the Plasco tower with full cracked and/or detached from the frame memebres; in other words the model assumes complete absence of slab and its composite action. This grillage model offers insight into the behavoir of structre at its lowest possible global stiffness.

The thermal properties and mechanical properties at elevated temperature are considered as per Eurocodes. The fire started on the 10th floor and travelled horizontally within the floor and vertically to upper floors, eventually leading to its collapse. The thermo-mechanical analyses performed in during this early study assumes various fire spread scenarios, including horizontal spread within the floor and vertical spread to the top floors as shown in Figure 2

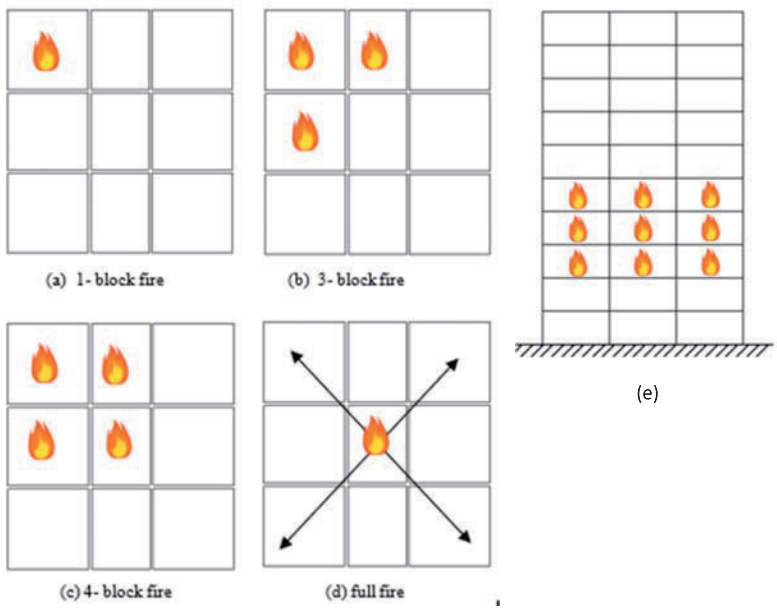


Figure 2: (a), (b), (c) and (d) represent different extents of fire spread in single floor analyses; (e) and (f) shows plan and elevation of multiple floor fire spread zones

Thermo-mechnical analyses have been performed on this model to understand the failure mechanism of Plasco Tower by considering various single floor fire exposures and a multiple floor fire exposure. Considering the thin members of trusses uniform temprture rise of 800^{0}C for all memebers has been considered.

Upto Sept, 2019

The amount of work completed by the end of Sept, 2019 was done to gain insights into..

- The effect of extent of fire spread in horizontal direction on the runaway failure temperature of the floor.
- The effect of pulling-in forces exerted by sagging floors on the columns on the global structural stability

In case of single floor fire, it is noticed that the failure temperature is governed by the extent of fire spread in horizontal direction. It is observed that the fire exposures involving 3 or 4 blocks of the plan (see Figure 2) is enough to cause a similar magnitude of floor deflections as caused by the full floor fire.

In multiple floor fire exposure, the overall behavior of the structure is governed by the "pulling-in" forces exerted by sagging floors on the columns which can eventually lead to collapse.

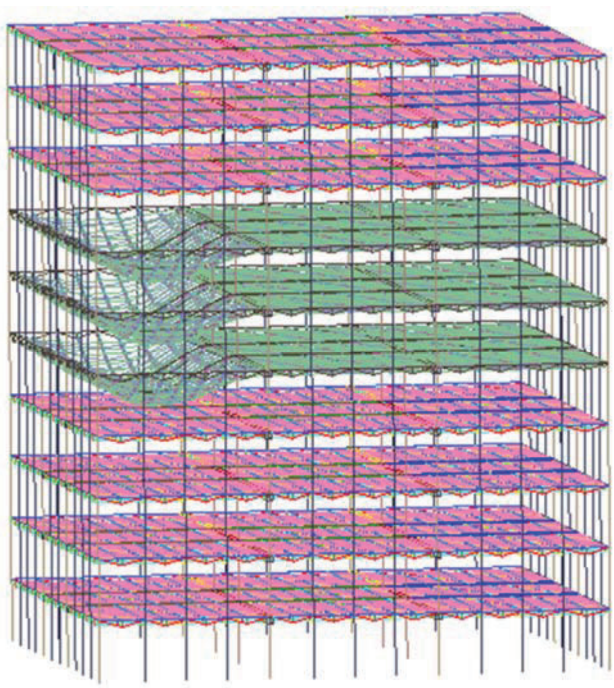


Figure 3: The sagging floors in multiple floor fire exposure analysis demonstrates how sagging floors exerting "pulling-in" forces

This analysis has provided some understanding into the behaviour of the Plasco Tower during the fire accident, and the potential failure mechanisms are not dissimilar to those discovered in the context of WTC Towers collapse [11, 12].

Oct 2019 – Jan 2020

There is a need to analyse the behaviour in greater detail including the investigation of potential composite action and more realistic fire scenarios as may be gleaned from the video evidence available. The present on-going work is focussed on modelling the slab which was ignored in the earlier model.

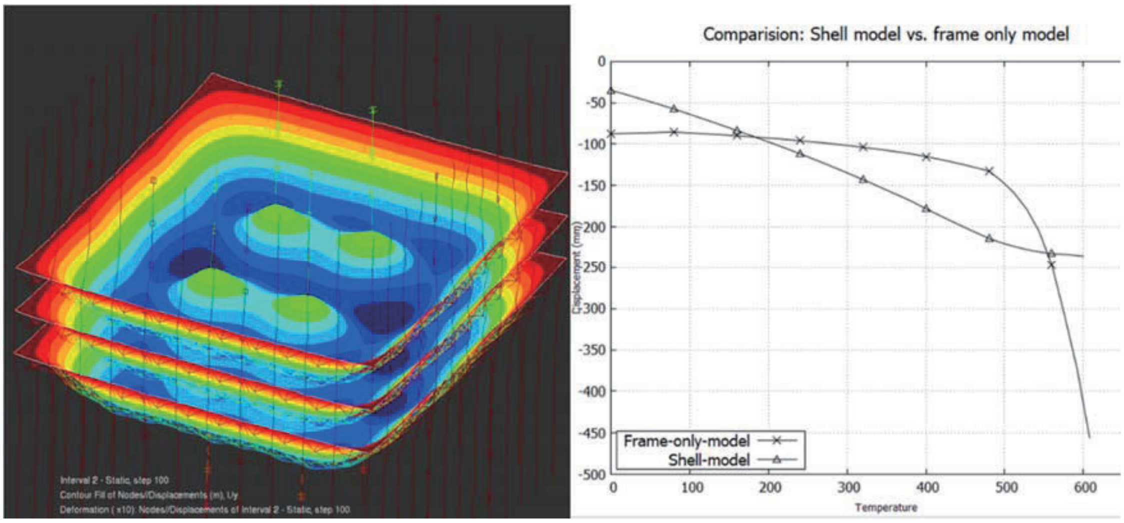
Modelling of the Plasco floor system to include the slab action has posed a challenge in the beginning. To avoid potential instability errors a simple elastic material has been used for the shell elements. Initial attempts have been made by modelling shell elements at an offset from frame members and then tying them up with frame elements using rigid links. This exercise generated tens of thousands of rigid links between nodes of shell elements and frame elements.

The analysis using this technique has turned out unfruitful with erroneous results, though further investigation needs to carry out to understand the reasons.

Later instead of using rigid link constraints, both shell elements and frame elements have been modelled on a same plane. The meshing of shells and frames have been done carefully to have nodes at common locations and merging them resulted in a computationally simpler model.

The model at this stage has shells elements included only in the floors where temperature load has been applied. After prolonged troubleshooting activity and solving various errors, stability in the thermo-mechanical analysis has been achieved.

Figure 4 shows the deformation response simulation of the composite action Plasco tower model when frame elements are subjected to 800^0C; top and bottom face of the shell elements to 250^0C and 400^0C.



(a) (b)

Figure 4: (a) Deformation contours in the Plasco floor systems (b) maximum floor deformation comparison in non-composite and composite floor systems

These analyses have shown the response of floors when modelled with full composite action. The deformations have greatly reduced in comparison to non-composite floor system though the material model used is inaccurate. This composite model has been developed with assumptions of elastic material model for concrete and arbitrary temperature distribution across the slab thickness. Further study is needed to understand accurate behaviour.

Conferences attended/attending

Conference	Title	Period
CONFAB 2019 (3rd Conference on Structural Safety under Fire and Blast 2019)	Ramakanth Domada, Tejeswar Yarlagadda, Liming Jiang, Asif Usmani (2019). Preliminary analysis of the collapse of Plasco tower under fire using OpenSEES. In CONFAB 2019, *3rd International Conference on Structural Safety under Fire and Blast Loading, Proceedings*. London.	Sept 2-4, 2019
ISSC 2020 (Indian Structural Steel Conference 2020)	To be held at IIT Hyderabad, India. To be published by Springer Special Conference Proceedings	March 25-27, 2020
SiF 2020 (11th International Conference on Structures in Fire)	"Preliminary analysis of the Plasco Tower collapse in fire using OpenSEES," submitted to SiF 2020, Brisbane, Australia (pending acceptance)	June 24-26, 2020

Significance

Understanding the failure mechanism that lead to the collapse of Plasco tower under fire is important because of the behaviour of structures in fires involves many counterintuitive and subtle phenomena in the thermo-mechanical response of large frame structures which are not well understood, even by experts in the profession.

Structural fire resistance design relies heavily on behaviour of materials at high temperature which has skewed the attention of professionals towards seeking explanations of structural phenomena primarily in material response. While not wrong, this over-reliance on the material aspects often make engineers lose sight of structural system response.

For example, investigation of the collapse of World Trade Centre, New York Buildings in 2001 following the terrorist attack provided valuable lessons on fire safety and structural stability of tall buildings.

This was generally true of the multiple explanations for WTC collapses that surfaced after the event. Usmani [11, 12] and his research team at the University of Edinburgh found that the WTC towers had an unusual vulnerability to large fires. The team was able to produce a credible collapse mechanism, which did not depend upon any gross assumptions about the fire or failure of connections or even structural damage. A clear stability failure mechanism was established by conducting a simple computational analysis. In addition, the analysis was entirely consistent with the fundamental principles developed previously during the simulation of Cardington tests led by Usmani et al. [13].

Therefore, this leads to question whether the collapse of Plasco tower, just like WTC, was due to an unknown mechanism or not.

Greater understanding and knowledge of large structural frame performance in fire can only be gained by rigorous analysis, just as it is customary to determine the response of structures to earthquake or wind loading.

Future work

a. Better modelling of the Plasco building in OpenSEES
    - Realistic fire loading scenarios will be developed
    - Appropriate non-linear material model for concrete slab will be applied
    - Dynamic analysis will be performed
b. Development of appropriate fire loading definition for Plasco building
    - Vertical and horizontal travelling fire scenarios will be developed. The ETFM framework will be used Dai [14] for the parts of the structure where it is valid.
    - Inter-compartment fire spread models will be developed based on photographic and video evidence.
c. Automation of temperature data transfer from OpenFOAM model
    - Heat transfer analysis for Plasco tower compartments will be carried out
    - Transfer of node temperature histories from OpenFOAM to OpenSEES

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