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OpenFIRE: An Open Computational Framework for Structural Response to Real Fires

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Abstract

More than 1300 new buildings over 200m tall have been built since the year 2000, representing 80% of the total number of supertall buildings globally. The proliferation of such challenging architecture in densely populated urban environments has led engineers to question the fitness of the prevalent prescriptive approaches in ensuring the safety of occupants in the event of a fire. This paper proposes a more rational methodology to estimate scientifically appropriate boundary conditions to represent realistic fire scenarios on the structure for more credible simulation of the consequent structural response using an integrated computational tool. An open-source framework, “OpenFIRE” is developed to implement the methodology. OpenFIRE is capable of simulating the whole sequence i.e., development of a fire scenario, heat transfer to the structure, and the thermomechanical response of the structure, through a sequential coupling of CFD tools with FE software. OpenFIRE exploits the capabilities of available tools such as FDS and OpenSEES and integrates them to produce a free, efficient, and open source computational framework which allows to customise and modify the source codes. It can bring structural fire community a step closer towards the adoption of performance-based designs (PBD). This framework is validated by comparing the thermal and structural responses of a square hollow section (SHS) steel column under fire with the experimental data. The critical parameters of the fire scenario produced by the framework are found in close agreement with the experimental data. The thermal and structural responses of the SHS column exposed to the developed fire scenario are also validated with test results in terms of structural temperatures, failure modes, and failure load.

Keywords: OpenFIRE framework**,** integrated simulation, open-source software, progressive collapse

1. Introduction

Fire is a severe threat to urban environments and accounts for a very large proportion of economic losses and mitigation costs on society. For instance, in the USA the total cost of fire in 2014 was estimated at $328.5 billion, or approximately 1.9 % of US GDP [1]. Provision of adequate fire safety in the built environment requires inputs from many science and engineering disciplines, however with little communication between them. For over one hundred years practically all global engineering practice has continued to define a fire environment as a standard time-temperature curve [2]. This has traditionally been considered to be a conservative representation of a fully developed fire scenario in compartments. However modern materials and architecture have changed so fundamentally that this assumption is being seriously questioned, particularly in the context of tall buildings and large open plan spaces preferred in modern office towers [3–5]. These large compartments bear no resemblance to the approximately 3m cube compartment on which the "standard fire" is based. The tragic events of September 11, 2001, in New York were a watershed, when three tall steel-framed buildings collapsed, partly or wholly because of fire, for the first-ever time. There have been several major events after this event involving fire in multi-storey buildings (e.g. the Plasco Building fire and the Grenfell Tower fire) involving loss of life and building collapses, often characterised by fires that were not predicted and therefore not considered in the original fire safety design. The realisation of the inadequacy of the current approach to quantify the likely fire hazard intensity has provoked new thinking and "idealised fire hazard scenarios" are being proposed [6] that would account more faithfully for features of real fires. For wider acceptance and adoption of these more scientific and rational approaches in fire safety engineering, a number of technical challenges must first be addressed, followed by training of engineers and regulatory reform. The current paper focuses on the twin technical challenges of accurately estimating the demand imposed by complex fire scenarios on the structure and faithful simulation of the structural response using an integrated computational tool. None currently exist that enable seamless automated simulations of accurate fire hazard demand and structural response.

Computational structural engineering is a mature field with numerous software options available to model every kind of "loading". Commercial software offers advantages (extensive verification & validation, professional support, user-friendliness, etc.). However, development of commercial codes is often dictated by the requirements of the most profitable applications and rarely addresses the needs of academic researchers, thus developments typically lag well behind research. In the context of international collaboration, even discounted costs can inhibit joint working and deter new entrants to the field. Another option is to use proprietary software developed by researchers. Well-known examples of such codes in the context of this paper are: SAFIR (University of Liège) [7], Vulcan (University of Sheffield) [8], and ADAPTIC (Imperial College London) [9], all of which can be used for the analysis of structures subjected to fire (and also earthquakes in case of ADAPTIC). Due to limitations of a tightly bound architecture resulting from procedural programming paradigms prevalent at their inception, these codes can be increasingly difficult to maintain and develop over time, making them unsuitable for a devolved community of developers. Furthermore, because they are often developed by a small team of dedicated researchers at the original host institution, they are typically not open source. These limitations are being overcome by the development of open-source alternatives that use object-oriented programming (OOP) [10]. A successful example of this is Fire Dynamics Simulator (FDS), a free and open-source CFD software package developed by National Institute of Standards and Technology (NIST) of the United States Department of Commerce [11], it is the most widely used CFD software in the world for fire simulations. Another good example is OpenSEES [12], originally developed at the University of California, Berkeley for simulation of structural response to earthquakes written in C++ (available for free download at opensees.berkeley.edu) has spawned a rapidly growing community of developers who have added to its capabilities over the past two decades [13,14].

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Often fires are observed to travel across floor plates in large buildings, as seen in the WTC Towers in 2001, the Madrid Windsor Tower fire in 2005, and the Faculty of Architecture building fire in TU Delft in 2008. In the case of the Grenfell tower fire in London (2017) and the Plasco Building fire in Tehran (2017), the fire travelled vertically to the upper floors. These are many other complex fire scenarios which further need to be explored to get a more realistic simulation of fire. It is practically impossible to simulate the structural response to the aforementioned complex fire scenarios with the currently used software tools without an enormous investment of time and effort. Furthermore, due to the uncertainties embedded with fire, fire cannot be modelled a-priori. Therefore, the development of a practical methodology such as OpenFIRE is essential to enabling a fully performance-based approach to structural fire engineering. Most of the commonly used commercial software packages lack the required features for more customised applications or introduce new fire models, and researchers do not usually have the freedom to implement them in the source code. OpenFire is developed as a fully open-source framework by integrating open source CFD and FE software which will be available to the profession and the community of researchers and developers for use and further development.

Although some attempts have been carried out couple the CFD with FEM, however source codes for most of them are limited to the host institutions and/or compatible for commercial packages only. The proposed methodology and computational framework OpenFIRE integrates free, efficient, and open source computational tools: FDS from NIST[11]; and OpenSEES software from PEER, University of California, Berkeley[12]. For complete analysis, OpenSEES is used to conduct thermal and structural analysis and FDS for producing a realistic fire scenario. To couple the CFD and FEM tools, a middleware – Fire Structure Data Mapping (FSDM) – is also developed by utilising an open-source programming language (python). FSDM middleware is used as a data mapping tool to provide an interface between OpenSEES and FDS software. The middleware is capable of mapping the data from the CFD simulation correctly to the right location in the heat transfer and thermo-mechanical models of structural geometry by generating relevant parts of the script files. This feature of the middleware makes the structural analysis of tall buildings seamless and straightforward. Two different approaches are presented in the proposed methodology to exploit the data from FDS. This kind of fully open-source framework can be freely and independently updated and improved by other researchers. Its primary use, however, will be in facilitating simulations of large structural models under realistic fire scenarios, including the progressive collapse of tall buildings such as the three towers of World Trade Centre (WTC) and the Plasco building. In this paper, OpenFIRE is validated with an experimental and numerical study considering a simple case of a square hollow section steel column exposed to a pool fire. OpenFIRE will enable even small or mid-level consultancies to undertake large projects requiring performance-based engineering against the fire hazard for existing and new buildings. Due to open-source and licence free package, OpenFIRE can be used and further developed by research community and engineers based on their requirements.

2. State-of-art approaches for modelling structures in real fires

2.1 Computational packages for structures in fire

Much of the activity on modelling and simulation of structures in fire stems from the Broadgate Phase 8 fire in the UK [15], which led to the seminal full-scale fire tests at Cardington during the mid-1990s [16,17]. The six Cardington tests produced a great deal of excellent data, which led to a tremendous spurt of research activity in this field in many UK and European universities and research institutions. Franssen et al. [18] presented one of the earliest loaded frame analyses also carried out at Cardington but preceding the full-scale tests. Some of the earliest efforts in explaining the findings of the full-scale Cardington tests, primarily through simulation and modelling, were by Bailey [19], Rose et al. [20], Wang [21], and Huang et al. [22]. The Cardington tests allowed the validation of a number of finite element software packages and simulation approaches such as ABAQUS, Vulcan [22], SAFIR [7], ADAPTIC [23] and hybrid simulation approach [24–26]. The collapse of the WTC towers on 11 September 2001 spurred on further studies on progressive collapse of tall buildings in fire. The studies carried out by official investigator NIST [27] concluded that the buildings would have survived the aircraft impact without collapse had it not been for the fires that followed. Indeed one of the buildings in New York (WTC 7) that did not suffer any aircraft impact (except minor damage from falling debris) did collapse because of the fires started following the collapse of WTC1 [28]. In recent years, more cases of structural collapse in fire have taken place around the globe, such as the partial collapse of the Faculty of Architecture Building in Delft University of Technology [29], and the collapse of the Plasco building in Tehran on 19 January 2017 [30,31]. Further studies on understanding the progressive collapse in fire have been carried out by Agarwal and Varma [32] and Sun et al. [33]. To understand the failure or collapses and performing realistic structural analysis idealised fire models are crude and over-conservative. Realistic structural behaviour in fire can be accurately simulated by performing CFD and FEM analysis. As discussed, some researchers attempted to carry out the structural analysis, however no single package available which is totally licence free and open-source that can be modified and improved by the designer and engineers. This paper proposed such package which makes the whole process seamless.

2.2 Existing attempts for coupling CFD-FEM

Despite the developments in computational techniques to understand fire behaviour and structural response in fire, there are certain factors to which a great deal of uncertainties with the evolution of fire and its behaviour are embedded; such as fire load, ventilation condition, fuel type, fuel distribution, compartment geometry, velocity (especially in travelling fires), and so on [4,34–38]. While there are several idealised models to represent the effect of fire, such as the standard temperature-time curve, the parametric fire curve, and the hydrocarbon fire curve but these models are perhaps too idealised to reflect the real fire behaviour. To achieve full performance-based engineering (PBE) approach for a structure under fire, it is necessary to use realistic fire models as inputs to the heat transfer models. Short of carrying out expensive full-scale testing one may use CFD (computational fluid dynamics) techniques, which are steadily improving with improved research input to their development and validation against experiments. CFD solves the transport equations (continuity, momentum, and energy conservation) which keep the energy conserved throughout the whole process of the fire and provide spatiotemporal boundary conditions for structural analysis. The classical models to obtain the time-temperature history, such as Kawagoe's equation [39], standard fires, parametric curves [40,41], and localised fires [42], do no not present the energy conservation for the whole process of fire especially during the decay phase [4]. However, it is worth mentioning that even the most advanced fire models use the simplifications of the gas-phase combustion and do not explicitly present the pyrolysis and phase-change combustion of the solid fuels. Most of fire-simulations are highly sensitive to the specific parameters (ventilation, fuel type, spread rate and so on), and the modelling results can deviate from the realistic fire events [43]. The input parameters required to represent a particular fire scenario must be accurately provided by the designer or engineers. Therefore, while using the CFD codes to present the fire scenario, user must have sufficient knowledge and understanding of the limitations and uncertainties involved in the CFD modelling [44]. The 'real fire scenarios' may be developed based on the experimental studies [45] or reconstructed by calibration process, however in both cases "real fire" is basically a *'user defined'* fire that is modelled through a physics-based approach.

In recent years, CFD is considered as the most suitable, economical and accurate approach for developing a realistic fire scenario. Unlike the idealised fire models (standard fire curves, parametric fires), CFD-FE coupling offers a very detailed resolution that may provide a more informed analysis while maintaining principle of energy conservation for the whole process. Work on coupling realistic fire models with the structural model accelerated after WTC disaster in 2001 to better understand the structural fire response and since then structural community started to recognize the potential of producing a realistic fire scenario. To simulate structural response under realistic fire conditions, three models need to be developed, (a) fire model, which may be a CFD model, (b) thermal or heat transfer model, and (c) thermomechanical model. However, the sequential coupling of all these models is a complex task. The key complexity of simulating the structural response during fire arises from the enormous difference in the relevant length and time scales associated to fire and structural models. This leads to significantly different computational approaches involving very different grid configurations and resolutions in both spatial and temporal domains. Because of this difference in the spatial and temporal resolution of fire and structural domains, it is a challenging task to couple CFD and FEM models. The characteristic time for a fire model is much lower than a solid model, however, the meshing in CFD could be even larger than the thickness of structural elements. The heating of solid depends on the thermal inertia which varies with the conductivity and specific heat of the material [46]. In a study, Jowsey [36,47] presented a range of characteristic heating times for various solid materials. Furthermore, performing such a fine mesh in CFD is not practical and computationally very expensive. A few methodologies have been proposed which are capable of coupling CFD models with FE models prepared using commercial FE software. These techniques have their advantages and limitations. Over the last two decades, researchers have worked to develop suitable methods to couple FEM with the CFD model, which should not only be more accurate but also computationally cost-effective. To achieve a fully coupled simulation of structural response under fire, quite a number of approaches have been proposed. These coupling approaches include algorithms, new techniques, different ways of couplings, types of fire, and data mapping methods [48–52]. Prasad and Baum [48] proposed a method, called Fire-Structure Interface (FSI) by employing a zone-model approach to investigate the effects of radiative heat transfer from combustion products on a structure and couple FDS results with ANSYS and utilise this approach to investigate the collapse of the WTC. Prasad and Baum [48] assumed unit emissivity in the upper layers, these assumptions are practical for post-flashover fire. Silva et al. [50] proposed a methodology (FTMI) and coupled ANSYS with FDS, however, this model is limited to ANSYS scripts.

If CFD can be used to satisfactorily simulate the net heat fluxes at solid boundaries, then a reasonable estimate of the thermal exposure history of structural members can be determined from finite element heat transfer analyses. However accurate estimation of convective (dependent on the velocity and length scales) and radiative heat transfer coefficients – by-products of the optical properties of gas phase in fire affected by the emissivity, wavelength, extinction coefficient, and so on [36] – at the boundaries is highly uncertain in the dynamic environment of a fire. An effective approach was proposed by Jowsey [36] for estimating convective, radiative and total heat fluxes on fire exposed boundaries from a CFD simulation. Jowsey's approach is based on gas conditions near the exposed surface and analysis of the smoke layer and products of combustion allow heat fluxes to be defined based on smoke absorption coefficients and temperatures. To produce accurate boundary conditions for conducting a heat transfer analysis, a concept of Adiabatic Surface Temperature (AST) was introduced by Wickstrom [53,54]. Conceptually, AST represents the surface temperature of a perfectly insulated surface when exposed to the same conditions as real surface. AST can be considered as effective fluid phase temperature which can be employed to calculate both radiation and convection heat transfer. Although the AST method is a robust, practical, and simple method to obtain boundary conditions at the structural surface for thermal analysis, its applicability depends on the optical depth. Optical depth must be thick enough to assume a single radiative source, unit emissivity, and therefore radiation losses from the surface can be neglected which allows to consider local conditions for the heat fluxes. It is highly unlikely that such scenario is achieved in large compartment [35,55]. A review paper of Khan et al. [4] presents the limitations and applicability various fire models including AST method.

Since the concept of AST was introduced, several researchers utilised AST concept while studying the structural behaviour in fire conditions. Banerjee et al. [56] also used the AST technique to calculate gas temperatures from FDS for heat transfer analysis of structural elements and to simulate a 3D structural behaviour under fire using ANSYS. In a similar manner, Alos-Moya et al. [57] analysed the failure of a composite bridge under fire by coupling CFD and Abaqus software. These proposed frameworks are limited to couple only the commercial FE software using which these frameworks were developed because of the compatibility of scripts and elements used in thermal and structural analysis. Furthermore, these tools are generally limited to the small group of research team and not further developed or provide any opportunity to fire engineers and research community to improve them. In this regard, OpenFIRE enables the coupling of FDS model with an open-source FE software (OpenSEES) and gives full freedom to structural fire engineers which may be required for unique structures. Furthermore, the proposed methodology is not limited to couple FDS and OpenSEES, it can easily be implemented to any CFD and FEM packages.

2.3 Realistic fire Vs 'Idealised fire model'

It is subject of argument among structural community whether to utilise code-based fires or move towards computational techniques. As discussed in the previous section that the fire curves presented in internationally recognised standards and codes, were proposed several decades ago and largely based on the idealised small compartment fire tests and depends on empirical or semi-empirical relationships. Since then there have been attempts to develop more realistic idealised fire models, for example, "travelling fires" for large open plan floor plates [6,58,59]. Moreover, our understanding of fire behaviour and fire simulation methods and approaches are improving with the advancement in the field of fire science. Apart from the complications in performing experiments to produce empirical relationships such as code-based fires, there are various questions which are yet to be resolved within the available fire models, some of them are listed below:

- These fire models do not explicitly consider the type of materials stored inside the compartment, which strongly influences the dynamics of fire [60,61]. The process of pyrolysis would be different for each material which would be based on the volatility and stoichiometric requirement of the fuel. This process affects the growth and severity of the fire which is not taken into account in the idealised fire models.
- Generally, code-based fires are capable of producing reasonably accurate time-temperature data for ventilation-controlled fire scenarios. Whereas, Thomas curves [62] shows that fire behaviour is highly unpredictable in fuel-controlled fire scenarios.
- There is no information on the distribution of fuel load (pattern and location within the compartment), which plays a decisive role in defining fire growth, severity and travelling behaviour [61,63].
- Each building is unique in terms of its interior and architecture, and code-based fire models do not account of the building geometry which can be a governing factor in defining the fire behaviour [34,61,64,65]. Especially, the innovations in architectural designs to produce aesthetic designs can greatly influence the pattern and extent of fire propagation. The effect of geometry must be considered while quantifying the fire load for conducting the structural analysis [66]. In a travelling fire test (Malveira fire test [34]), it was observed that HRR suddenly increased due to the thermal feedback from the smoke layer when the fire reached near the beam soffit.

Although most prevalent fire protection engineering is still code based, however, due to the above-mentioned shortcomings of code-based fires, a detailed risk assessment is recommended before commencing fire engineering strategies for any occupancy. The true response of complex structures to real fires cannot be determined using currently prevalent fire models. Realistic and high-fidelity fire scenarios can only be generated by using CFD tool if accurate input parameters that can represent the physical model for fire simulation are used. It is imperative to resolve the boundary conditions with a high degree of fidelity to understand the thermomechanical response of complex structures [67]. It is possible by using the CFD that can answer the above questions in a much more convincing manner. In this paper, a robust extendable open-source framework (OpenFIRE) is proposed which is capable of producing a realistic fire scenario and performing a consequential thermomechanical analysis of structures to understand the structural response to fire.

2.4 Fire simulation output

FDS [68] is the most widely used CFD software in the world for fire simulation to solve practical problems as well as study the fire behaviour for research purposes. As discussed in section 2.2, to obtain boundary conditions with detailed resolution FDS is exploited by the structural community for understanding structural behaviour in fire. For solving compartment fire, FDS utilises the Large Eddy Simulation (LES) turbulent model to solve the smoke transport in the fire. In LES, energy and momentum equations of the large eddies are solved directedly, whereas the eddies smaller than the mesh size are modelled [44]. Therefore, FDS simulations are mesh sensitive, and it is required to carry out numerical tests for sensitivity analysis. A few methods are presented in [44] to determine the appropriate mesh size for a practical problem.

FDS is capable of providing the required data for analysis such as gas temperatures, velocities, wall temperatures, etc. However, it is imperative to understand how data can be extracted from FDS before using it for heat transfer analysis of any structure. In the current methodology, two major approaches available in FDS [69] are used to get the necessary data for thermal analysis. One uses *'BNDF'* which allows recording data of specified quantity such as heat flux, wall temperature, AST, etc. at all solid obstructions. Another method utilises '*DEVC*' namelist, where user provides the specific location and orientation of the quantity to be calculated [69].

Although the computational cost increases significantly because a large amount of data is produced, as '*BNDF*' records the desired quantities at all control volumes, therefore, there is no need to rerun the FDS analysis for extracting data at another locations. The major drawback of *DEVC* approach is that if data access is required at locations other than predefined in the model, fire simulations must be rerun. DEVC approach is a computationally efficient way of performing the FDS simulations as it calculates the desired quantities only at specified location compared to the *BNDF* approach which estimates the responses at all control volumes at solid boundaries [69].

Generally, only the fire compartment is modelled in FDS to simulate the fire behaviour as it has no interaction with the rest of the building. Whereas the thermomechanical model requires the whole structural model for the analysis of structural fire response. Therefore, the global coordinates for both compartment FDS model and whole structure heat transfer model must be the same irrespective of their geometrical extent to correctly map the required data from FDS to FE model at specified locations.

3. Development of the OpenFIRE framework

In recent years OpenSEES has been exploited to simulate the thermo-mechanical response of structures in fire. A number of researchers have been working with OpenSEES to develop an integrated capability to simulate the structural response to idealised fire scenarios such as standard fires, natural fires, localised fires, travelling fires. In the current paper, a framework is proposed to integrate OpenSEES with CFD, which describes how OpenSEES can employ a *user defined* output from the FDS (CFD model) as more realistic boundary conditions for heat transfer analysis and conduct subsequent structural analysis [70]. For fire analysis, firstly heat fluxes or temperatures need to be estimated at the surface using an FDS model. Secondly, heat transfer analysis must be carried out by applying the temperatures or heat fluxes from FDS, which can define both modes of heat transfer (convective and radiative) on the structural surface. A user can define any quantity (or quantities) by using middleware to obtain thermal boundary conditions such as gas temperatures, ASTs, heat fluxes, extinction coefficients, convective heat transfer coefficient so on.

As discussed in section 2.2, despite its limitations AST concept is exploited by many researchers as thermal boundary conditions in their study without explaining its limitations [50,51,71]. To validate the current methodology with the experimental and published numerical study, in the current study, ASTs are recorded in the fire simulation which are used as boundary conditions for heat transfer analysis. At this point, authors would like to mention that in addition to the limitations and assumptions associated with AST approach discussed in section 2.2, the convective heat transfer coefficient evaluated in FDS for determining the AST and heat fluxes may be poorly defined for a cell. Generally, the boundary layer size is significantly smaller compared to the cell size which makes it very difficult to incorporate a proper calculation as FDS averaged a quantity over a cell volume. Therefore, it is required that the user must be aware of the limitation of the quantity that has to be used as thermal boundary conditions for structural analysis [4].

By using the AST as the thermal boundary condition, this paper intends to show how temperature history (or any quantity) can be transferred from the gas phase to the FEM model as an effective thermal boundary condition (time-temperature history of a whole process for a *user-defined* fire scenario) [67]. Details and derivation of AST concept can be found here [53,54]. Finally, after conducting the heat transfer analysis, the temperature histories at various locations are transferred to the structural model to perform the thermo-mechanical analysis.

3.1 Couplings in OpenFIRE

3.1.1 CFD-HT coupling

After conducting the fire simulation, the output data are required to be transferred to the heat transfer (HT) model using a suitable coupling technique. Figure 1 shows the overview of the OpenFIRE framework. Details involved in CFD-HT coupling are explained in this section. While generating the heat transfer model in OpenSEES, the heat transfer entities are required to define a particular shape of the section and entities must be assigned unique IDs, each entity requires all information about the section such as length, section dimensions, entity type, coordinates, etc [70].

In OpenSEES 2D heat transfer model, while defining an entity there is no need to explicitly provide global coordinates to the entity whereas local coordinates at elemental level such as its centroid and dimensions are required. The device locations *(DEVC or BNDF*) are assigned with orientations in FDS by employing the middleware. The middleware arranges the devices in the same sequence as entities arranged in the OpenSEES model to get thermal load for heat transfer analysis. Therefore, the script files for both FDS (devices) and OpenSEES (entities) can be generated simultaneously using the middleware maintaining the same sequence for the entities and devices. To establish a coupling between FDS and OpenSEES software, the temperature history (AST) generated by FDS software is mapped to the heat transfer model in OpenSEES. It enables the heat transfer model to pick the correct file from FDS data to apply as thermal boundary conditions based on the device output corresponding to the ID of each entity generated by the OpenFIRE framework. The ASTs generated by devices in FDS model are used as thermal boundary conditions for corresponding entities in heat transfer model by mapping the data obtained from FDS at the correct location in a heat transfer model. A module of the middleware post-processes the output data from FDS and assigns proper indexing to each file to transfer as boundary condition files for HT analysis. This approach significantly makes the process seamless and error free, especially when structural analysis for a large model needs to be performed.

On the other hand, when heat transfer along the length of the member plays a significant role in overall member temperature, a 3D heat transfer analysis is recommended. To apply the FDS time-varying output data at the correct location in the heat transfer model, the FSDM (detail in section 3.2) program identifies the suitable entity lying in that particular range of coordinates where the device data was recorded in the FDS model. In this case, entities are being mapped by the middleware depending upon their global coordinates.

The major difference in data transfer for both types of heat transfer analyses is that in 2D heat transfer analysis, the global coordinates need not be assigned. The HT entities are created with specific IDs and local coordinates. These unique IDs of entities are used to map the data from corresponding device of FDS model. However, for 3D heat transfer analysis, entities are created using a similar global coordinate system for FDS and the heat transfer model. In this case, the global coordinates in a heat transfer model are used by the middleware to map the entities corresponding to the location of installed devices in the FDS model. Therefore, unlike the entity IDs in 2D analysis, entities are mapped using the global coordinates in the 3D heat transfer model.

3.1.2 HT-TM coupling

Once heat transfer analysis is finished, the output from OpenSEES is obtained as boundary conditions for structural analysis in the appropriate format. A component of middleware searches the nodes within a range of coordinates and generates a node-set in the structural model corresponding to each HT entity output. Furthermore, for each node-set, an element set is generated where the output from corresponding HT entity (after heat transfer analysis) is applied to conduct thermomechanical analysis (details are described in section 3.2).

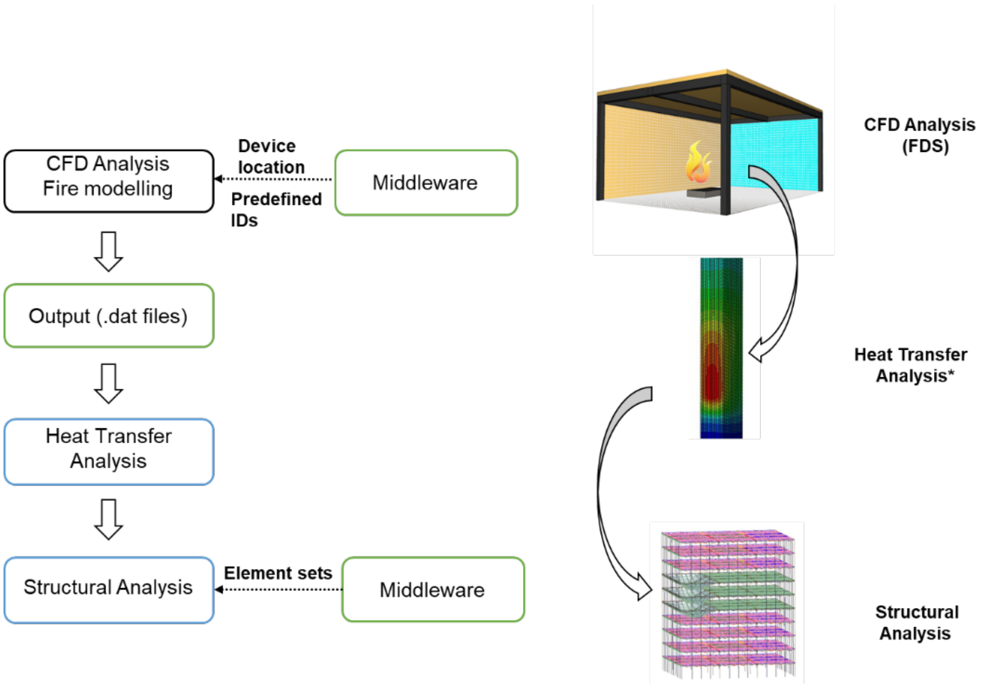

Figure 1: CFD-FEM coupling in OpenSEES

3.2 FSDM (Fire Structure Data Mapping) middleware

To map the FDS data to OpenSEES, a middleware named; Fire Structure Data Mapping (FSDM) is developed (executables of FSDM can be downloaded from [72]), which can transfer the time varying boundary conditions from FDS output to FE model for conducting heat transfer analysis by generating the heat transfer entities in the heat transfer model and corresponding devices in the FDS model. The steps involved in the FDS-FEM coupling for producing a real fire scenario ('*user-defined'* fire scenario) and conducting a sequential thermomechanical analysis is represented using the flowchart as shown in Fig. 2. The FSDM includes a series of modules which are written in the python programming language (all source-code can be downloaded from [73]). The exposed surface on the heat transfer FE model is identified by the middleware to which the AST data from FDS model is mapped as thermal boundary condition for heat transfer analysis. Similarly, the heat transfer results are also mapped to the structural model for conducting thermo-mechanical analysis using the developed middleware. Once the fire simulation is complete, the middleware converts the time-temperature history (or any other quantity as a function of time) in an appropriate format as required by OpenSEES program (*.*dat* format, space separated files) and implements them at the desired locations to carry out the heat transfer analysis. However, for structural analysis data mapping is not as straight forward as for the heat transfer analysis. Structural models consist of nodes and elements to represent the surface of a structural members, whereas the heat transfer model in OpenSEES is developed using HT entities (explained in detail in section 3.1.1). To accurately map the data from HT to structural model, the middleware searches the elements in the structural model and creates element sets corresponding to each HT entity output file. Fig. 2 shows the flow of the various steps involved in the OpenFIRE framework using the FSDM middleware. The architecture of the integrated computational framework for conducting sequential FDS analysis, heat transfer analysis and finally structural analysis is illustrated in Fig. 3. Following are the various steps which are performed in this open-source framework to conduct an FDS-FE coupled analysis.

1) In the first step, FDS devices and HT file are generated. This module of the FSDM also creates node sets in the structural model based on the corresponding location of the entity in heat transfer model. This module then searches all the elements corresponding to each node set and creates element sets where the heat transfer output is to be applied (Figure 3). The FSDM can be employed for structural models developed using any type of elements such as beam column elements, shell elements and continuum elements.

2) Before carrying out FDS simulation, geometry of the fire compartment needs to be produced by writing input code in FDS. In FDS, structural surfaces are defined as *obstruction* (*OBST*) and necessary fuel load needs to be defined in the code as shown in Fig. 3. For data extraction as discussed in section 2.4, *DEVC* or *BNDF* approaches can be utilised by describing them in the FDS code. To attain proper thermal gradients, it is recommended to place the 'Temperature thermocouple (Solid phase Device, AST)' as close as possible if utilising *DEVC* approach (for BNDF data can be extracted after simulation as discussed earlier in section 2.4), however, it depends on the users' discretion, who decides based on the requirement for the level of accuracy and computational cost. The devices at specific locations are generated using the framework and added to the FDS input file. Now, FDS simulation is carried out to get the fire scenario based on the user input ('*real fires*'), and the data in the form of AST (HF or gas temperatures) is generated for conducting heat transfer analysis (see Fig. 2 and 3).

3) After the FDS simulation is finished, FDS dumps the output of the simulation. Now, one of the main functions performed by the FSDM middleware is to process output data from FDS to convert it into a suitable format (*.*dat* format) as required by OpenSEES to conduct heat transfer analysis (see Fig. 3).

4) In OpenFIRE framework, the FSDM middleware generates the appropriate *HT entity* in OpenSEES heat transfer model for each device data in FDS model and implements corresponding AST data to it as shown in Fig. 2 and 4. The obtained output from FDS can be applied as boundary conditions for conducting heat transfer analysis by using '*User Defined'* command in OpenSEES [70]. The heat transfer model generated by the OpenFIRE framework selects correct FDS output file and applies it as thermal boundary conditions at each entity to perform heat transfer analysis to get the temperatures inside the solid material (solving heat diffusion equation).

5) Once the heat transfer analysis is complete, a component of FSDM post process the HT output data as required for conducting thermo mechanical analysis [72]. Now, the post processed output from heat transfer can be directly applied to the specific element sets created in step 1. Fig. 4 shows the application of a HT entity output (arrow) to an element set (square) in the thermomechanical model.

6) Finally, using the time-varying temperature history, a thermo-mechanical analysis is conducted to understand the response of a structure exposed to a real fire scenario (user-defined fire scenario) (Figure 3).

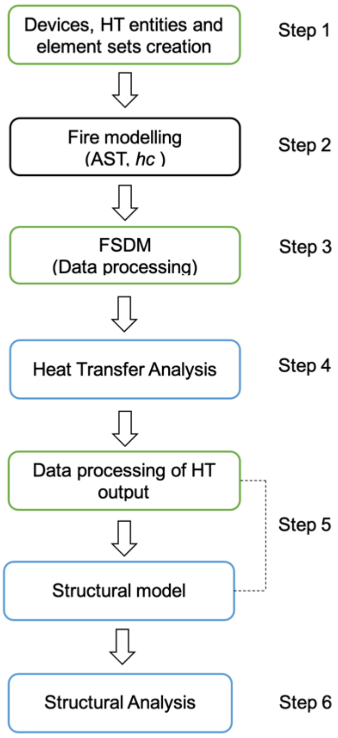

Figure 2: Steps involved in novel OpenFIRE Framework

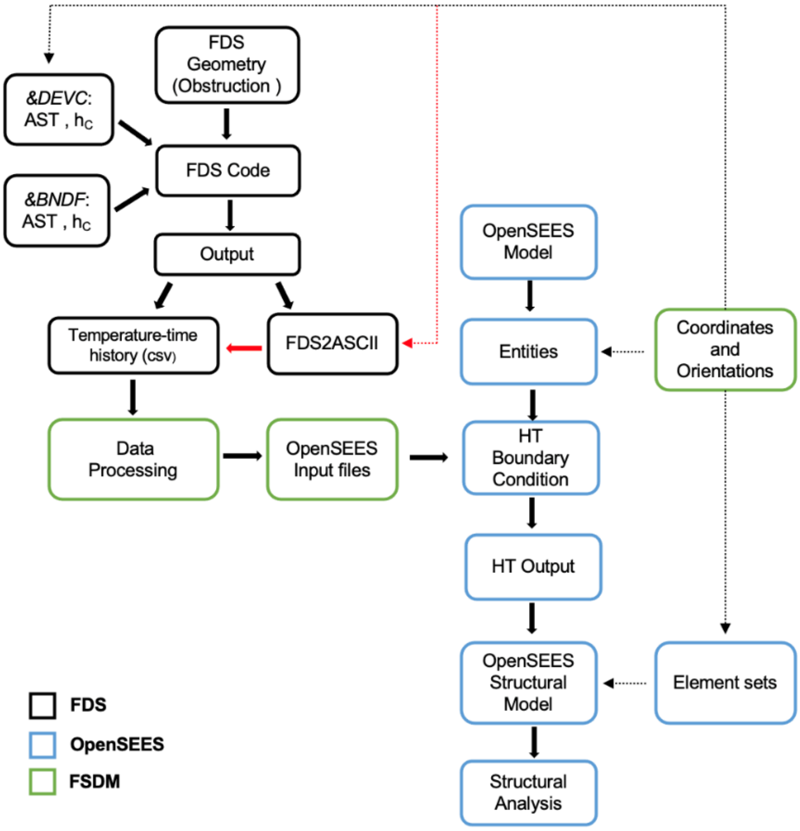

Figure 3: OpenFIRE Framework

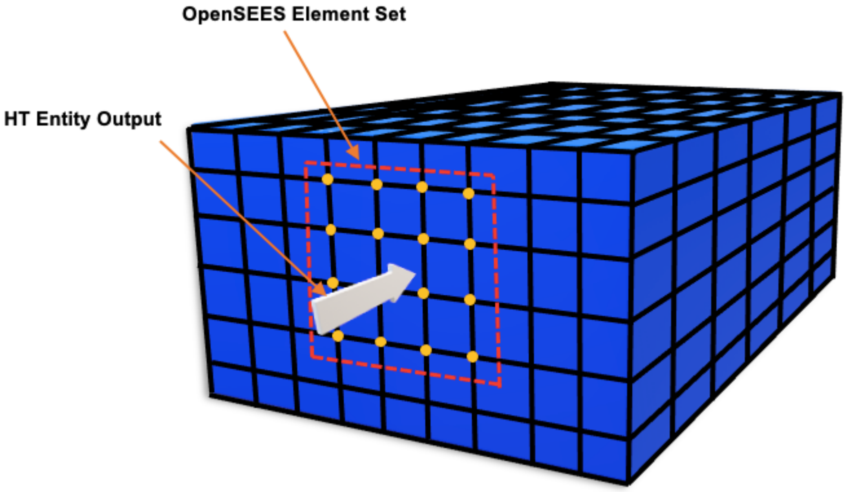

Figure 4: OpenSEES Entity and Element Set

The key features of this FSDM middleware are as follows:

- The FSDM middleware uses HT entity IDs to map the FDS device output data to OpenSEES heat transfer analysis.
- For coupling of heat transfer model with thermomechanical model, FSDM creates element sets in the thermomechanical model corresponding to each entity output, so it is independent of the mesh size of the FE model and it can be used for any discretization level. Besides, the mesh size of the FDS model and FE model needs not to be same.
- The code written for developing FSDM middleware is generic, and it can be used in models made with any kind of structural elements such as beam-column (linear), shell elements (planar) as well as brick elements (continuum).
- The middleware can be applicable to map different types of output from FDS such as gas temperatures, heat fluxes and so on.
- All source codes are freely available to use and further develop by the designers and researchers [73].

4. Implementation and validation of the OpenFIRE framework

In this section, OpenFIRE framework is implemented and validated using experimental and numerical results. A square hollow section (SHS) column which was experimentally tested by Kamikawa et al. [74] and used by Zhang et al. [51] for validating their coupling of FDS with a commercial FE software (Abaqus). The objective of using this particular structure is twofold. Firstly, it enabled the validation of the current approach with an experimental study in terms of producing an accurate fire scenario and also validating the structural response of the member. Secondly, comparing the results with the numerical study of Zhang et al. [51] shows that the open source framework developed here is equally capable to a framework that was developed using a commercial package. The SHS column is modelled using displacement beam-column elements because, in future, OpenFIRE framework is aimed to be utilised to analyse the behaviour of large structures exposed to fire. Since modelling of large structures using high-resolution elements such as shell and solid elements is computationally expensive, therefore, simpler and computationally economical beam-column elements would be utilised. This experiment was also validated by Zhang et al.[51] to couple a commercial software with an FDS model, therefore this case of column exposed to pool fire is chosen to validate the OpenFIRE framework. The objectives of this validation are to demonstrate various capabilities of the OpenFIRE framework such as prediction of a realistic fire scenario and understanding response of structures exposed to these realistic fires through seamless coupling of CFD and FE software.

4.1 Fire Scenario

To validate the framework, the thermal response of the SHS steel column exposed to a pool fire is predicted using an FDS model. The fire model is developed using the data obtained from the experiments [74]. In the experiment, an SHS column (STKR400) of 0.1 m x 0.1 m and 1.6 m tall with a thickness of 3.2 mm was exposed to a pool fire. The authors performed four tests under various loading and restraint conditions. The base of the columns was fixed for all cases. To validate the framework with experimental and numerical results, only Case 1 and Case 4 are considered in this paper. In Case 1, except at the base, the column was unrestrained along the length and at the top as illustrated in Fig. 5. These experiments were mainly performed to measure the thermal expansion of the column when exposed to fire and to observe the bending behaviour due to thermal gradients. In all experiments, the columns were exposed to fire (one hour) until temperatures and displacement reached a steady state. However, in Case 4, as shown in Fig. 5, a restraint was applied to the horizontal movement of the column towards the fire source. Moreover, once the temperature of the steel column reached a steady state, which was around 52 minutes after ignition, a vertical force was applied and increased progressively during the experiment.

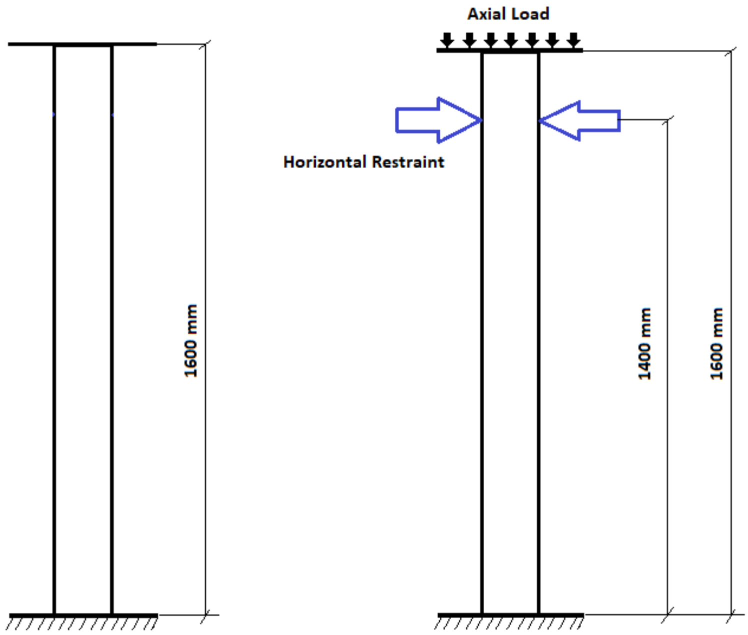

Figure 5: Loading and restraint conditions for Case 1 and Case 4 Kamikawa et al.'s test [74]

A 0.3 m square diffusion fuel burner of 0.25 m high was placed near one face of the column, as shown in Fig. 6a. Propane was used as a fuel which produced a heat release rate of 52.5 kW. The heat of combustion for propane (44715 kJ/kg) is obtained from SFPE Handbook [75]. In fire simulation, the soot yield for propane is taken as 0.1836, radiative fraction and solid angles are taken as 0.35 and 100, respectively [76]. Detailed information about the experimental setup can be found in the published article of Kamikawa et al. [74] and Zhang et al. [51]. A number of devices are installed on all four faces of the column in the FDS model to record temperatures around the periphery. The concept of AST has been utilised to get the output from the FDS model, which is exploited as a thermal boundary condition for further heat transfer analysis in the FE model. In addition to devices, ASTs were calculated at each cell of column by using *BNDF* namelist in FDS. To validate the data with the numerical results of Zhang et al. [51], the grid size of 0.015 m was used after a sensitivity analysis. The computational domain for the fire simulation was 0.75 x 0.45 x 1.8 m^3 as shown in Fig. 6. It is worth noting that in such fire scenario (localised fires) it is highly unlikely that emissivity of the gases reached one, therefore the assumptions of unit emissivity in AST concept may produce conservative results, especially at the upper part of the column (away from the flame and smoke).

Khan, A.A., Khan, M.A., Zhang, C. *et al.* OpenFIRE: An Open Computational Framework for Structural Response to Real Fires. *Fire Technol* (2021).
https://link.springer.com/article/10.1007/s10694-021-01184-0

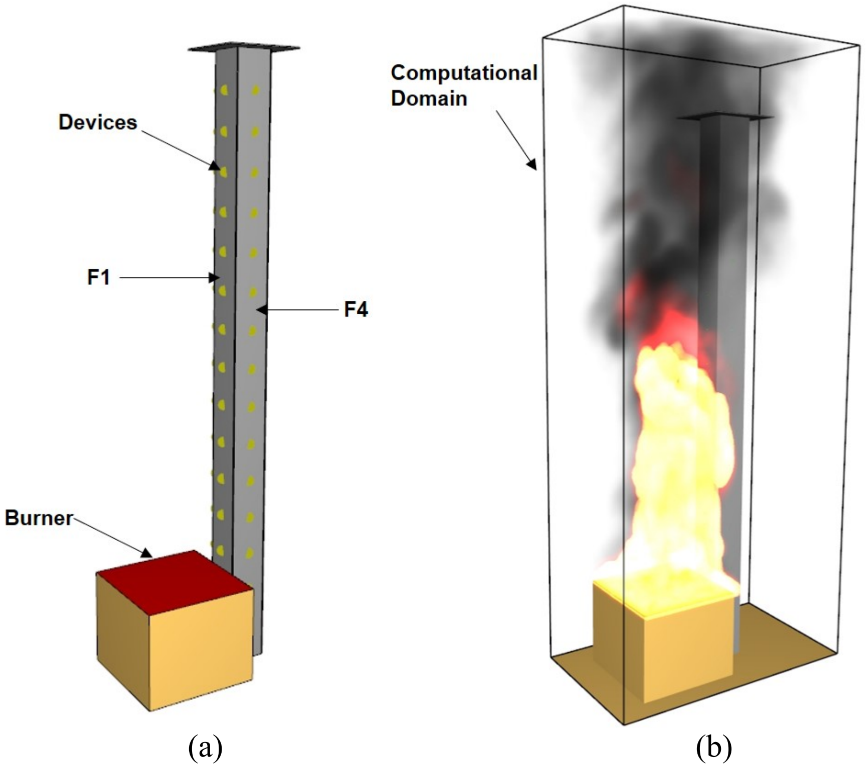

Figure 6: Model setup similar to experimental [74] **and numerical model** [51] **(a) geometry and device location (b) computational domain and smokeview (FDS)**

4.2 Thermal response of the column

The heat transfer modules in OpenSEES [77,78] are used in this paper to calculate the transient temperature evolution in the SHS column. As the fire simulations are being performed using FDS models, the subsequent heat transfer analysis for the specimen has a fully three-dimensional behaviour i.e., the temperature varies in all directions and this behaviour is included in this study. Furthermore, the conduction of heat along the length of the structural members and across the width and depth is also considered. Hence a 3D heat transfer analysis is carried out considering a separate HT entity for each thermocouple device data from the CFD model.

The SHS column (STKR400) of 0.1 m x 0.1 m and 1.6 m tall with a thickness of 3.2 mm is modelled using *brick* heat transfer entities in OpenSEES [70]. Various thermocouples devices are modelled in the FDS model along the length of each face at a spacing of 100 mm. Therefore, each column face is modelled using 16 heat transfer entities and the whole column comprised of 64 heat transfer entities. In this study, different faces are referred to as F1 to F4 as shown in Fig 6. The temperature-dependent material properties of steel (specific heat and conductivity) are in accordance with Eurocode [79]. *CarbonSteelEC3* material classes available in OpenSEES heat transfer module is used for modelling steel SHS [80]. Entities for all four faces of SHS are applied with thermal boundary conditions as AST produced by the FDS model at respective locations. The developed FSDM middleware as explained in section 3.2 is utilised for the application of the AST data from the FDS simulation as thermal boundary conditions for heat transfer analysis. ASTs are the gas phase temperatures which are calculated by assuming an adiabatic surface near the actual solid surface. For heat transfer in the solid, ASTs are used to calculate the heat fluxes, which required inputs for both convective and radiative heat transfer coefficients [4]. The convection coefficient of 25 W/m^{2}K according to the Eurocodes for [81] is assumed for fire-exposed surfaces. An emissivity of 0.7 is used in accordance with the Eurocodes for steel [81]. The temperature at various locations on all four faces of SHS column has been recorded after conducting a heat transfer analysis.

The predicted steel temperature distributions using FSDM middleware are shown in Fig. 7. Due to three-dimensional fire exposure, the temperature distributions are highly non-uniform across the section and along the length of the column. To validate the heat transfer model predictions, the simulated temperatures are compared to experimental results at four locations throughout fire exposure. At the centre of the front face and its corner, temperatures are measured at 400 mm above the burner and for side and back face, temperatures are measured at 600 mm above the burner. This comparison is presented in Fig. 7, which shows a reasonably good agreement between the experimental and predicted steel temperatures. The temperature at the front face is higher compared to other faces as it is directly exposed to the fire flame. Moreover, the temperature reached the corners and the side faces are highly influenced by the conduction from the front surface. The temperature at the back face is slightly lower compared to the experimental temperatures. This is due to the fact that the cavity radiation (heat transfer effects due to radiation in enclosures) effect is not included while conducting the heat transfer analysis. The experimental temperature reached the back face is in the range of 300 °C which does induce any loss of steel strength and neglecting the cavity radiation does not greatly influence the overall structural behaviour of the column.

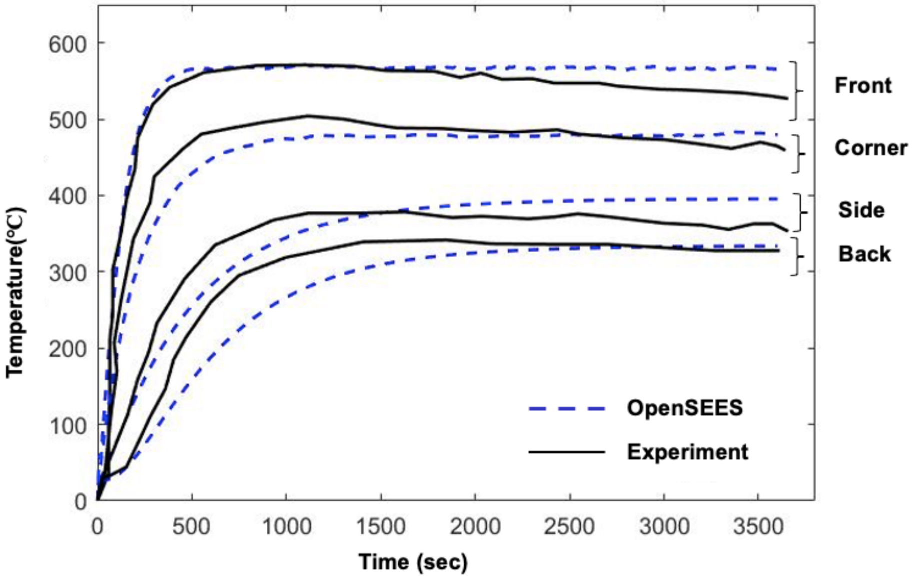

Figure 7: Comparison between measured and predicted steel temperatures in Case 1

4.3 Thermo-mechanical response of the column

To obtain the structural response from the novel OpenFIRE framework, a thermal stress analysis has been conducted by importing the temperature history from the heat transfer analysis. It is noteworthy that failure occurred due to global buckling and yielding of the column with yielding as a dominating failure mode. To trace these yielding and global buckling behaviours of the column, use of high-resolution 3D shell FE model is not required, and they can also be captured using less computationally expensive beam-column elements.

For structural analysis, the SHS column is modelled using displacement beam-column elements. A total of 160 elements of 10 mm length were used to model the full length of the column. The model is assigned with sections as *FiberSecThermal* available in OpenSEES. The *FiberSecThermal* section is defined using a total of four fibers, one fiber for each face [72].

Steel02Thermal steel material class with a yield strength (Fy) of 275 N/mm^2 is considered for the SHS column. The support conditions were applied to replicate the experimental setup as presented in Fig. 5. In Case 1, fixed boundary conditions are applied at the base of the column. Since the column is allowed to expand and bend, no vertical and horizontal restraint is applied along the column. In Case 4, to replicate the test conditions, a horizontal restraint at a height of 1400 mm is applied to avoid the lateral sway of the column, which might introduce additional P-δ (P-delta) moments. The AST boundary conditions from FDS to heat transfer were transferred using the FSDM middleware.

In Case 1 the column has no support at the top and is free to expand due to unrestrained thermal expansion. The displacement in vertical direction provided by the experimental results is used here to compare with the numerical results as shown in Fig. 8. In FE analysis, the maximum vertical displacement reached during the heating phase is 5 mm which is in close agreement with the experimental results as shown in Fig. 8. After the fire achieves a steady state and the temperatures remained constant (from 20 min to 60 min, Fig. 15), the vertical displacement also remains constant and starts to decrease during the cooling phase of the fire. An excellent match with the experimental results has been obtained for the entire duration of fire exposure, as shown in Fig. 8. While there is a slight deviation from 1500-4000s after the fire achieves a steady state, the temperatures remained constant in the FE simulation, therefore, no change in the axial displacement is observed. While, in experiment, temperature reduced slightly from 1500-4000s, which resulted a reduction in the axial displacement as shown in Fig 8. This difference in the temperature during 1500 to 4000s is responsible for a higher axial displacement in simulation compared to experiments.

In Case 4, the experimental work presents the vertical displacement at the column top and a discussion about the failure mode. The structural support conditions for Case 4 are more complex than in Case 1. Structural boundary conditions for Case 4 column are assumed as fixed at the bottom end, and the horizontal displacement is restrained at the height of 1400 mm. Nevertheless, to apply the load appropriately, the horizontal displacement at the column top should be restrained as it might change the position of the experimental apparatus. This could lead to the development of additional P-δ moments and can increase column instability. This instability is avoided by the increased magnitude of vertical loads as it applies some restraint to the horizontal displacements. In the FE model, the horizontal displacement at the column top is also restrained to simulate the above experimental loading effect. This analysis is conducted in two stages. In the first stage, the column is heated until the temperatures on all four faces are in steady state. In the second stage, a vertical concentrated load is applied at the top end of the column. The magnitude of the load is gradually increased until the column fails, and a failure load of 380 kN is predicted in the analysis, which is within 1.5 % of the failure load of 375 kN obtained from the experiment. Fig. 9 presents the comparison of time-vertical deflection behaviour from FE simulation with the test results for Case 4. The maximum vertical deflection and failure time obtained from the analysis is 5.4 mm and 89 minutes, respectively which are also in a close agreement with the experimental values of 5.6 mm and 90 minutes, respectively.

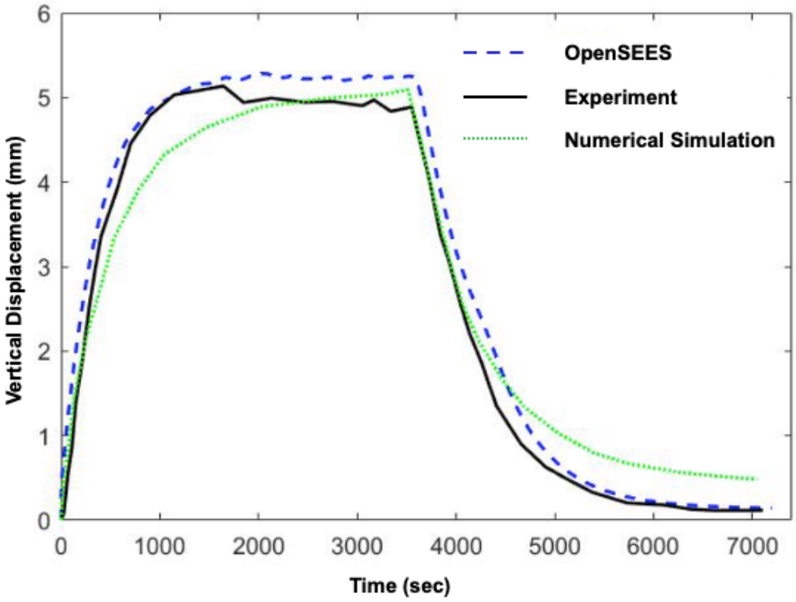

Figure 8: Comparison between measured and predicted vertical displacements for Case 1

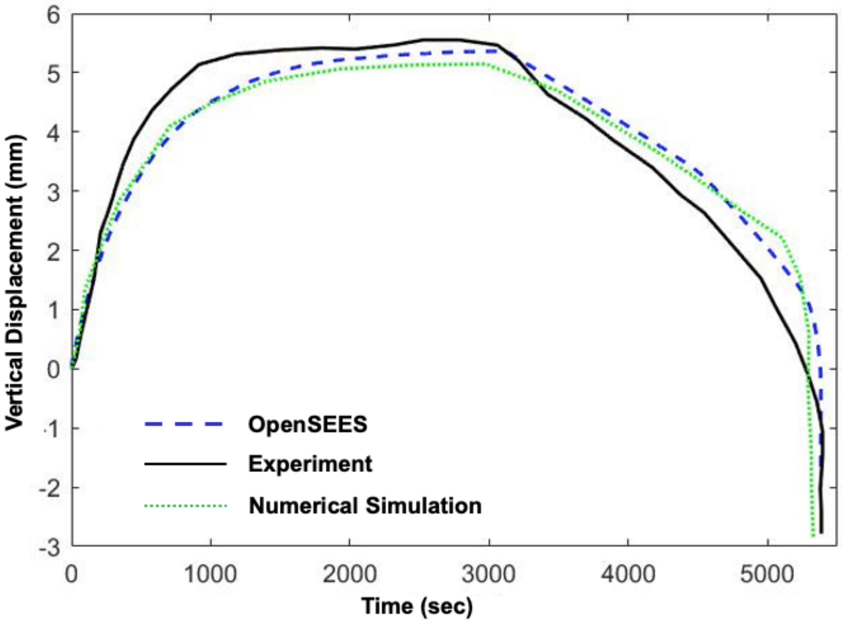

Figure 9: Comparison between measured and predicted vertical displacements for Case 4

It is noteworthy that this framework utilises displacement beam column elements for structural analysis, which reduces the overall computational expense compared to the structural model developed using shell or solid elements. Since, the OpenFIRE framework is intended to analyse behaviour of large structures exposed to fire such as tall buildings. To simulate the fire response of large structures, computationally efficient beam column elements are considered as the most suitable choice. Therefore, in this validation, beam column elements are utilised to simulate the behaviour of SHS column within the OpenFIRE framework. It also enables the user to conduct a coupled CFD-FE analysis with all of its individual components available as open-source software i.e. FDS, FSDM, and OpenSEES. The coupling approach developed here presents the first fully open-source framework to analyse structural behaviour exposed to real fires. Since, this is the only open-source package available for coupling CFD with FEM software, it allows research community to use it freely and develop based on their requirements. This tool can bring us a step closer in the adoption of PBD in structural fire engineering.

Conclusion

Practices, to evaluate the structural resistance, that were adequate a few decades ago are deficient now due to the modern architecture of buildings. A widely accepted solution to this lag in engineering practice is the adoption of the more flexible performance-based engineering (PBE) approach. The integrated computational framework proposed in this paper directly addresses the need for significantly better simulation tools for structural and fire safety engineers to encourage wider acceptance of PBE concepts. Work reported in this paper has produced a "free to use" open-source tool for engineers to design the built infrastructure against the threat of fire. A novel open-source framework, OpenFIRE, is developed to integrate FDS and OpenSEES software. As FDS is capable of producing realistic fire scenarios (fire scenarios generated by user's inputs) which are an essential requirement for PBE approach, this framework enables the user to analyse the structure when it is exposed to these realistic fire scenarios produced by FDS rather considering a prescriptive fire scenario such as standard fire, hydrocarbon fire and parametric fire. This framework allows considering realistic fire load for conducting structural analysis and obtain performance-based designs of large structures (tall buildings). To validate the current framework, a validation study was also performed considering an SHS column exposed to a pool fire. This study showed that a realistic fire scenario was accurately generated and sequentially implemented to an SHS column as thermal loads using the OpenFIRE framework. The thermal expansions of the column in Case 1 scenario were accurately predicted, and the failure axial load as well as the vertical deflection in Case 2 scenario predicted using the OpenFIRE framework were also in agreement with the test results. The open source nature of the framework allows the research community (users and developers) to use it and develop it by further enhancement. Currently, the framework is being utilised to conduct a forensic investigation of the progressive collapse of the Plasco building by the fire engineering research group at the Hong Kong Polytechnic University. Various other applications of the framework may include studying travelling behaviour of fire in a large compartment and high-rise buildings and employ them to understand the structural fire response.

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