Use of LS-DYNA for Structural Fire Engineering

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1 Introduction

Structural response in fire is complex and can only be properly investigated using finite element analysis considering non-linear geometry and material properties. Full scale fire testing to investigate the real response of structural forms to severe fires represents significant risks to researchers and is also expensive and difficult to undertake effectively. Therefore, computational tools are necessary for the safe design of structures under fire conditions. The majority of the computational tools currently used for structural fire analyses use static solvers. Explicit dynamic solvers such as in LS-DYNA are rarely used even though they are capable of dealing with highly non-linear problems.

LS-DYNA is used within Arup for a range of complex non-linear assessment purposes, from seismic design to investigations of blast and vehicle impacts. Therefore, there is a benefit in extending its capabilities for use in the structural fire assessment domain. However, there is no benchmarking of LS-DYNA currently available in the fire science literature for such applications.

This paper presents an overview the work undertaken by Arup and Imperial College London to benchmark LS-DYNA for heat transfer and structural fire analysis of steel and steel-concrete composite construction against analytical solutions, other static numerical codes, and experimental data.

Multiple problems that encompass a range of thermal and mechanical behaviours in fire are simulated. They include 0D, 1D, 2D and 3D heat transfer of structural members composed of steel, concrete, and fire protection materials incorporating radiating enclosures and gaps subjected to heating under convective and radiative boundary conditions. The mechanical problems include 2D steel beams and frames, and 3D steel-concrete composite structures subjected to linearly increasing uniform heating, a standard fire, or a natural fire. A parameter sensitivity study is carried out to study the effects of various numerical parameters on the convergence to quasi-static solutions.

The use of LS-DYNA for structural fire engineering applications is demonstrated through applications to Arup commercial projects in the built environment sector. These include heat transfer studies of concrete filled steel columns and structural fire analyses of high-rise structures with unique geometries.

2 LS-DYNA benchmarking models

Since 2012, Arup Fire in UK has conducted an extensive series of LS-DYNA validation and verification studies (i.e. benchmarking) to enable the use of software for commercial structural fire engineering projects. Studies included: benchmarking of various material models; verification of the response of beam, shell and solid element types; and fundamental structural behaviour such as cantilever bending and column buckling at ambient and elevated temperatures. Furthermore, the fundamental structural response to high temperatures have been assessed, namely restrained thermal expansion, thermal bowing, and composite action effects.

In this paper, we report a summary of the case studies used for benchmarking of heat transfer and structural fire models.

2.1 Heat transfer

The objective of heat transfer benchmarking studies for fire engineering applications is to verify that LS-DYNA can be used to predict:

- the thermal response within materials typically found in structures (i.e. steel, concrete and fire protection materials); and
- heat transfer via radiation within an enclosure.

The geometry modelled within a heat transfer model will be part of a wider structure and construction build-up. Areas of interest will depend upon the construction being modelled and the reason and aims of the heat transfer study. They may include reinforcement within a concrete slab, a beam or column protected behind a non-standard protection proposal or whether a combustible component within a construction build-up is likely to reach charring or ignition temperatures.

LS-DYNA benchmarking studies conducted in Arup include simple transient 0D, 1D, 2D, and 3D thermal response cases compared to analytical solutions; and benchmark cases on fire exposed structures presented in SP Report 1999:36 [1]. A selection of benchmark studies is illustrated in Fig.1.

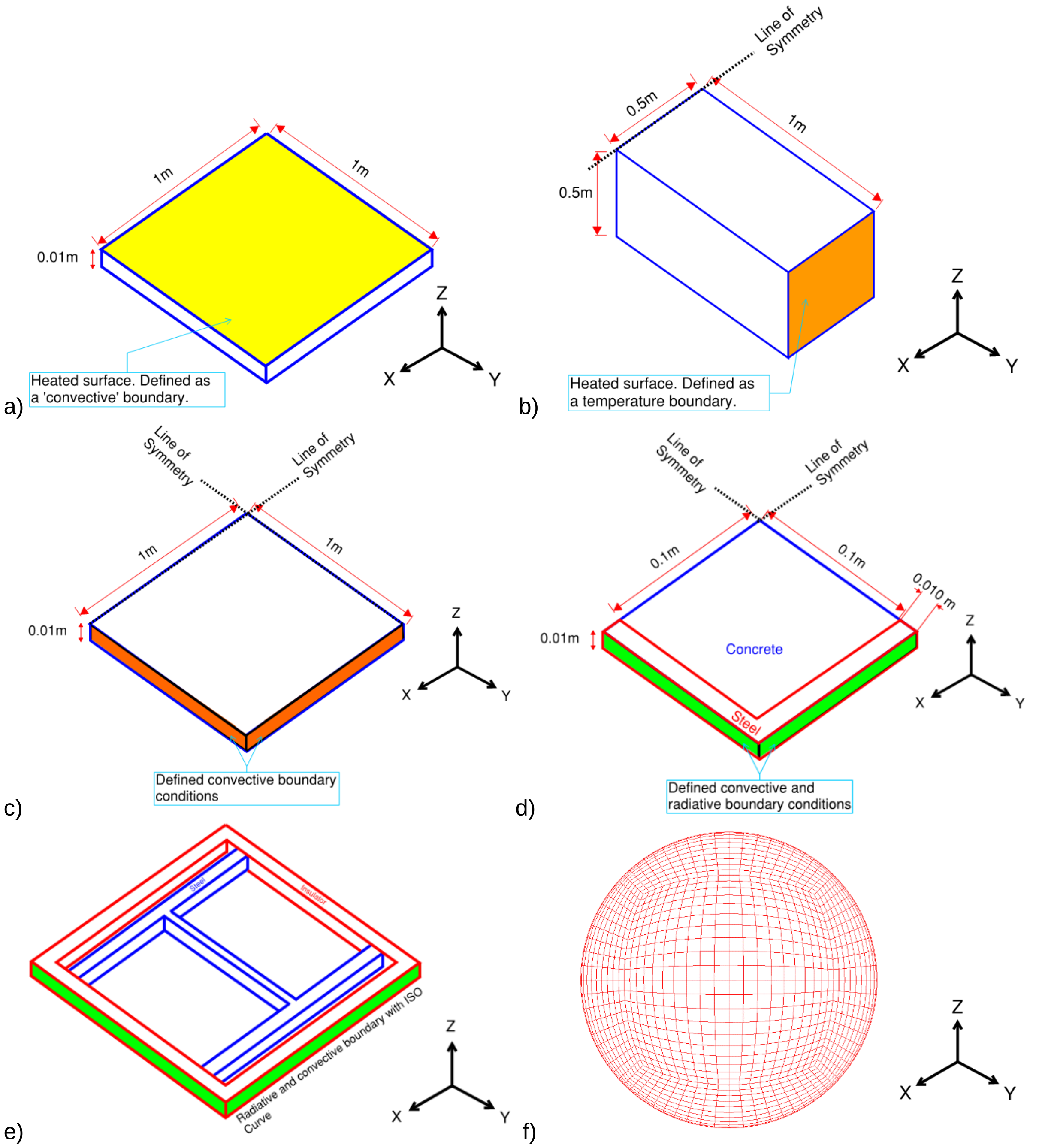
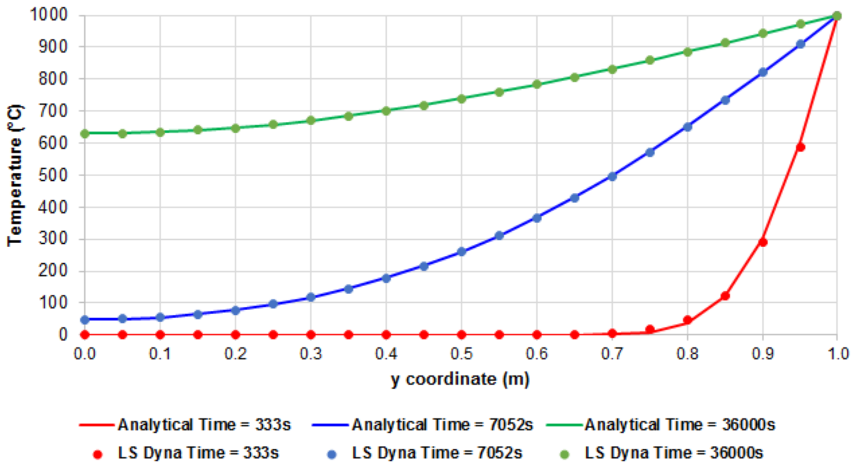


Fig.1: A selection of LS-DYNA benchmarking studies for heat transfer: a) 0D - lumped mass with convective heat transfer; b) 1D transient thermal conduction; c) 2D transient heat transfer; d) 2D transient heat transfer through multiple materials; e) heat transfer by thermal radiation in two voids of an insulated steel section; and f) 3D transient heat transfer.

For validation and verification studies LS-DYNA (LS971 R6.1.1) version has been used. Material models which have been verified include *MAT_T01_THERMAL_ISOTROPIC (constant material properties) and *MAT_T10_THERMAL_ISOTROPIC_TD_LC (temperature dependent material properties). A range of scenarios have been considered with varying boundary conditions which include nodal temperature input, convection, and convection and radiation (representative of a real fire) applied either as a constant boundary value or variant with time. Heating scenarios with element

temperatures going up to approx. 1100°C that could be expected during a fire have been considered. In total 13 different cases have been investigated and benchmarked.
Fig.2 illustrates a comparison of LS-DYNA predictions with analytical solutions and reported case results from SP Report 1999:36 [1] for two of the studies. It can be seen that the predictions from LS-DYNA match well the expected solutions. Similar observations have been made for all of the investigated cases.
A sensitivity study was undertaken to assist in our understanding of the impact of the Fourier number. Through these models it was been demonstrated that a model with a Fourier Number of 500 (element size of 0.002m and a timestep of 20s) returned predictions which were incompatible with the analytical solution. This corresponds with the advice given by Livermore Software Technology Corporation [2]. To date, all successful LS-DYNA predictions have utilised a Fourier Number between 0.00013 and 1.
In addition, for the majority of the case studies, models with coarse meshes (≥12.5mm for a solid element model with the dimensions of 0.1m×0.1m×0.01m) demonstrated non-physical behaviours within the early stages of the simulation (e.g. significantly higher than expected temperatures). This indicates that users must take care with choice of element size and time step to prevent unphysical over-estimation of material temperatures in highly exposed areas (e.g. the outer corner of a column) with high spatial and temporal thermal gradients. Similarly, for the case of radiative heat transfer within a void, the accuracy of the results are dependent upon the number of elements used to describe the void edge. Therefore, a sufficiently dense mesh based on a mesh density study must be used when undertaking an assessment of this kind.



a)

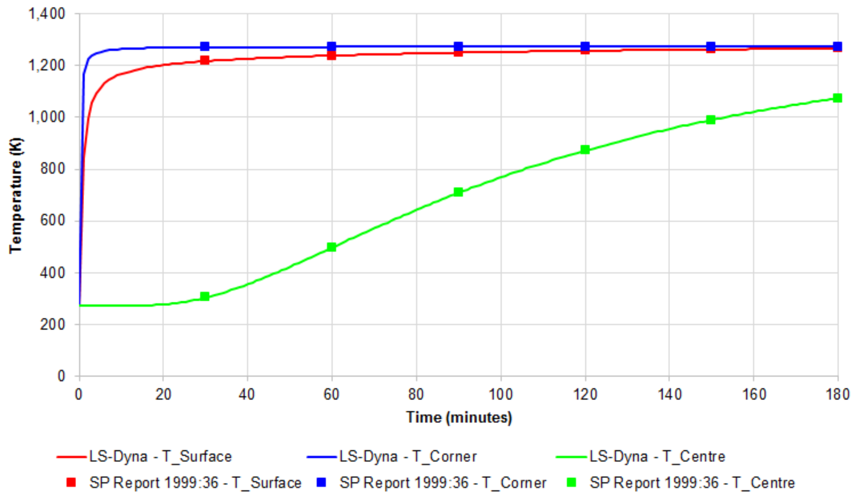


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Fig.2: Comparison of LS-DYNA simulation results with a) analytical solution for a 1D transient thermal conduction through a solid subjected to a fixed temperature boundary condition (Fig.1b); and b) reported case results from SP Report 1999:36 [1] for a 2D transient thermal conduction through a solid subjected to convective and radiative boundary conditions (Fig.1c).

In summary, in this benchmarking exercise conducted by Arup, LS-DYNA has been validated and verified for the following heat transfer problems:

- use of 3D solid elements to study transient 0D, 1D, 2D, and 3D heat transfer problems;
- conduction through a solid with temperature dependent and independent material properties;
- heat transfer between two solids in contact – perfect thermal contact using shared nodes and using a 'contact surface';
- symmetry and adiabatic boundary conditions;
- a constant temperature boundary condition;
- convective and radiative heat transfer to / from a fluid at a constant and time variant temperature;
- radiative heat transfer within a void enclosed by solids (through a non-participating fluid).

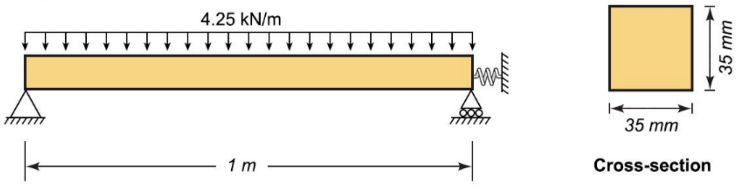
More details and results on some of the case studies can be found in Temple *et al.* [3].

2.2 Structural fire analysis

The objective of structural fire analysis benchmarking studies for fire engineering applications is to verify that LS-DYNA can be used to predict:

- structural response of different types of construction (e.g. steel beams and columns, composite steel framed building, etc.) subjected to severe heating;
- heat transfer within a radiating enclosure.

The structure modelled within a structural fire analysis model will be typically either a localised detailed model of different structural elements or connections between them, or sub-models of a whole building structure (e.g. a complete floor, elements of interest and structure surounding it) . Areas of interest will depend upon the construction being modelled, structural layouts, and likely fire scenarios. Typical fire scenarios can include but are not limited to localised fires (e.g. single item or a small area burning), full compartment fires (e.g. a whole room or series of rooms engulfed in flames) or travelling fires (where a fire ignites in one part of a compartment and then travels around consuming the available fuel in sequence).
LS-DYNA benchmarking studies for structural fire analysis conducted in Arup and Imperial College London include simple single steel beam/column models, 2D steel frames, and 3D composite structures. Results are compared to analytical solutions, a series of experimental results published in the literature, and other numerical implicit and explicit software. A selection of benchmark studies is illustrated in Fig.3.



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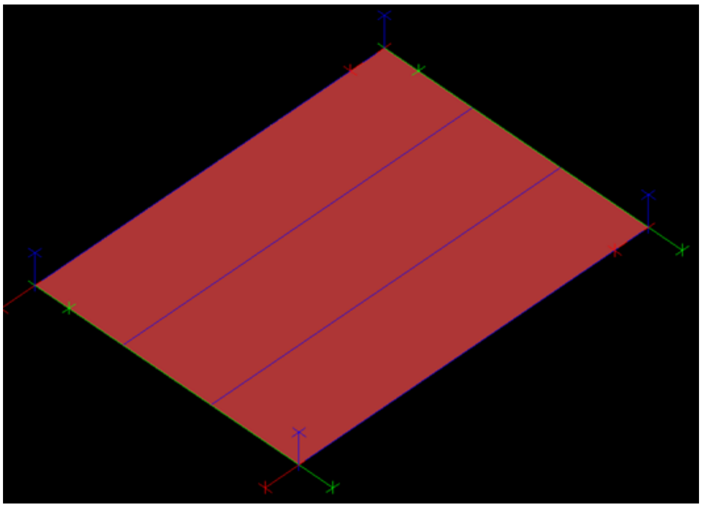
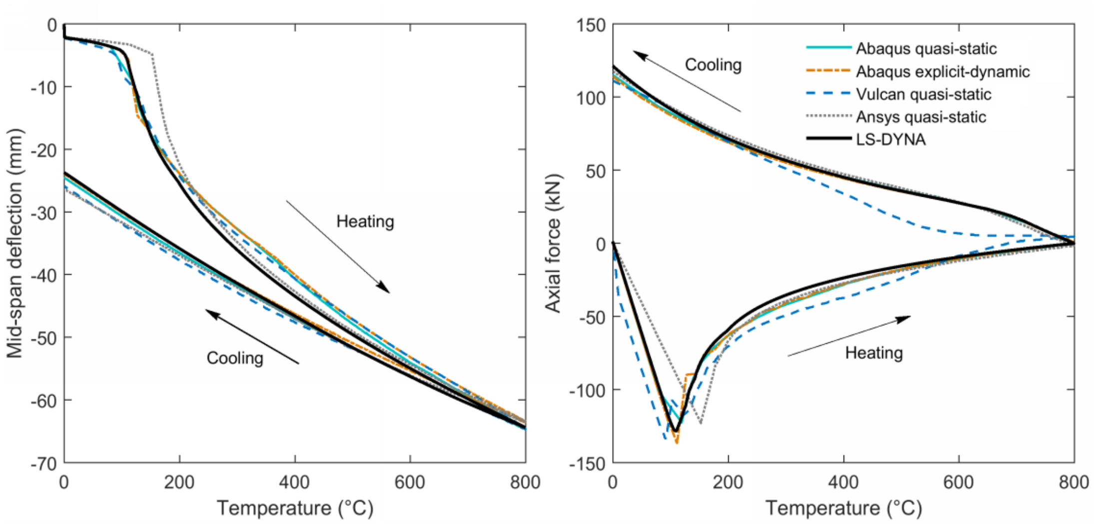


b)

Fig.3: A selection of LS-DYNA benchmarking studies for structural fire analysis: a) uniformly heated restrained rectangular steel beam; and b) composite concrete slab by steel beams subjected to the standard fire curve (ISO 834).

For validation and verification studies LS-DYNA versions LS971 R6.1.1 and R7.1.1 have been used. Material models which have been verified include *MAT_004, *MAT_172, and *MAT202. A range of scenarios have been considered with varying boundary conditions and levels of restraint, and fire scenarios. Type 1 (Hughes-Liu) beam elements, and Type 2 (Belytschko-Tsay) and Type 16 (fully integrated) shell elements have been considered. Extensive parameter sensitivity studies have also been conducted to investigate the effects on the results.
Fig.4 illustrates a comparisson of LS-DYNA predictions with solutions from other software packages and experimental results from Gillie [4] and Zhao *et al.* [5] for two of the studies. For the first case (Fig.4a) LS-DYNA predicts the development of heated beam mid-span displacements and axial forces with temperature well in comparison to other software packages (Abaqus, Vulcan, and Ansys [4]). For the second case (Fig.4b), model predictions are in a good agreement with the experimental results during heating. However, the model over-predicts the recovery of deflection during the cooling stage (i.e. at 120min). This could be attributed to the cracking of the slab that was observed after 90min and/or due to the difference between the boundary conditions applied to the model and the actual restraint applied to the test, which cannot be accurately replicated.



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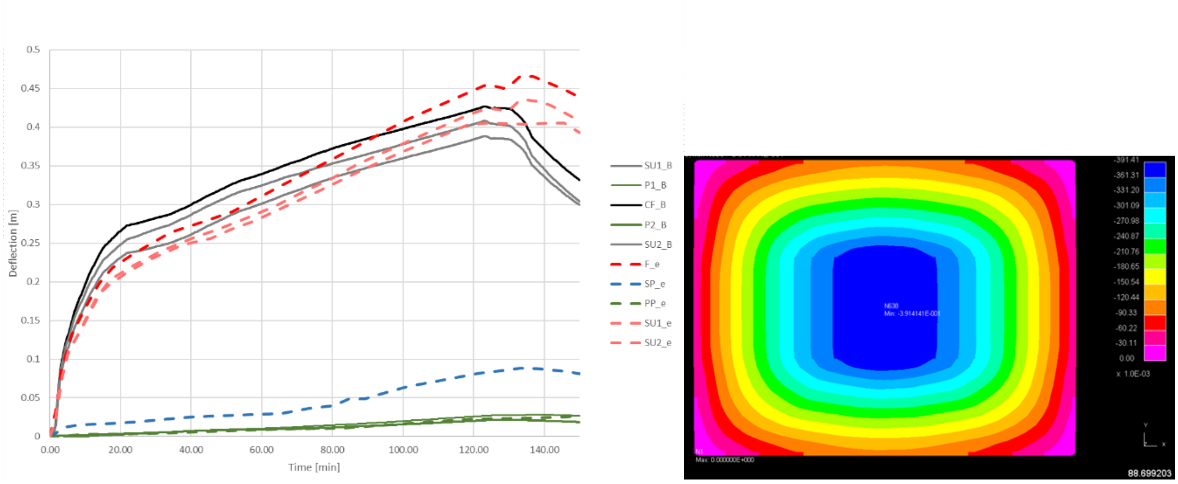

b)

Fig.4: Comparison of LS-DYNA simulation results with a) simulation results published by Gillie [4] obtained using different software packages for a uniformly heated restrained steel beam (Fig.3a); and b) experimental results published by Zhao et al. [5] for a composite slab (Fig.3b). Experimental results - dashed lines, and LS-DYNA model results - solid lines (Fig.b – left). Fig.b (right) indicates a deflected shape of the slab.

In general, results illustrated previously and from other benchmarks not reported in this paper indicate that explicit dynamic solver of LS-DYNA is able to capture the key phenomena of heated structures. For all benchmarks it is able to predict the development trends of displacements, axial forces, and bending moments with increasing temperature within acceptable level of accuracy. However, limitations and discrepancies have been observed for results when composite concrete slabs cool down after a fire event. A parameter sensitivity study has indicated high sensitivity of results to various parameters and that it has to be carried out for every model to ensure that LS-DYNA solution converges and is quasi-static.

In the benchmarking work carried out in Arup and Imperial College London, LS-DYNA has been validated and verified for the following structural fire engineering problems:

- uniform, and non-uniform heating boundary conditions;
- material non-linearity;
- geometric non-linearity;
- structural restraint from surrounding elements and stress redistribution;
- use of beam and shell elements to study structural response of steel and composite steel structures;
- thermal bowing;
- composite action in the concrete slab.

More details and results on some of the case studies can be found in Rackauskaite *et al*. [6].

3 Application of LS-DYNA to a real project

As identified previously, benchmarking of LS-DYNA in Arup has been conducted to enable the use of software for commercial structural fire engineering projects. In this section, application of LS-DYNA to recent project of a high-rise building in London is presented.

Arup were appointed to conduct a structural fire engineering assessment in order to provide an optimised structural protection scheme which meets the requirements of Part B3 of the UK Building Regulations. That is, to demonstrate that with optimised fire protection "*in a fire a structure should remain standing for a reasonable period of time*". To demonstrate the stability of the proposed structure with the optimised protection scheme under a range of different fire scenarios, the structure has been modelled using LS-DYNA.

The proposed building is a new 20 storey (75m high) commercial office building. The building and typical office floor plate are illustrated in Fig.5. Firstly, to conduct the assessment a number of different fire scenarios that are likely to occur in the building have been selected based on the time-equivalence study [7] [8] [9]. Then, a model of a typical office floor plate has been built in LS-DYNA as illustrated in Fig. 6. The goal of the model was to capture concrete tensile membrane action effects, deformations of the structure, changes in axial forces and bending moments within different structural elements.

In LS-DYNA, cellular steel beams and columns have been modelled using Type 1 Hughes-Liu 2-noded beam elements. Concrete slab has been modelled using Type 16 (fully integrated) 4-noded shell elements with reinforcement represented as a smeared layer across each element. Perfect composite action between steel beams and concrete slab has been assumed via shared nodes. Mesh of approx. 0.25m has been used based on validation studies and previous projects. Concrete core has not been included in the model and was represented by a fixed boundary condition. Temperature dependent material models *MAT_202_STEEL_EC3 and *MAT_172_CONCRETE_EC2 have been used for steel elements and concrete slab, respectively. These material models incorporate recommendations from Eurocode 2 and Eurocode 3 and have been validated to capture material non-linearities at high temperatures.

In order to accurately represent the restraint provided by the building columns on the floors above and below the modelled floor, columns one floor above and below the fire exposed floor have been fixed in translation; and columns 1.5 floors above and below the fire exposed floor have been fixed in rotation.

It should be noted that the upper part of the column is free to move vertically to allow load transfer from upper stories and to allow column collapse mechanisms to be observed.

Vertical displacements of the structure at the end of fire exposure are illustrated in Fig. 6. Use of LS-DYNA to model the structural fire response of the building enabled Arup to identify any critical areas of the structure, optimise the fire protection layout, and demonstrate that the structure can maintain its' stability under severe fires. It also enabled to gain a better understanding of structural performance which could not be estimated by following prescriptive guidance.

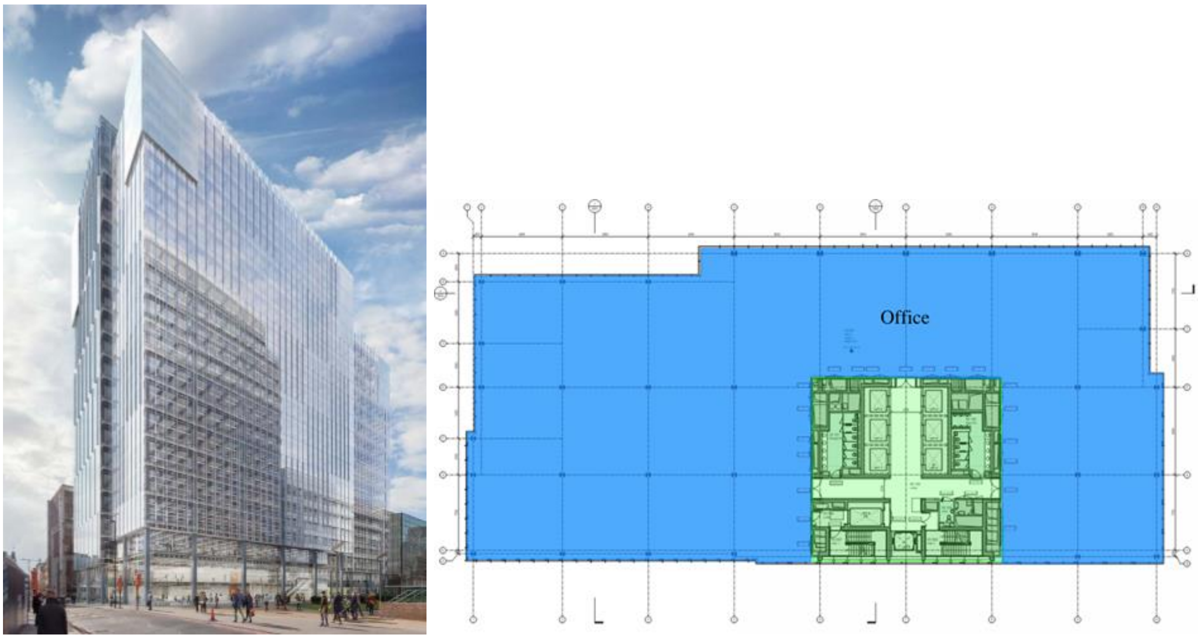

Fig.5: Rendering of the new high-rise commercial office building in London where structural fire engineering assessment using LS-DYNA has been applied (left); and plan of a typical office floor (right).

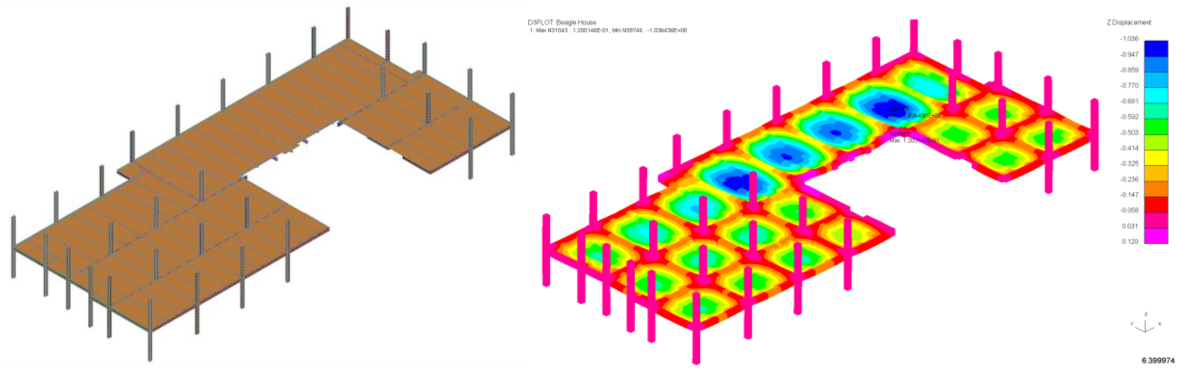

Fig.6: LS-DYNA model geometry of a typical office floor plate (left); and a contour plot of vertical displacements in the model at the end of fire exposure (right).

4 Summary

In this paper, an overview of the work undertaken by Arup and Imperial College London to benchmark LS-DYNA for heat transfer and structural fire analysis of steel and steel-concrete composite construction against analytical solutions, other static numerical codes, and experimental data has been presented.

It has been shown that LS-DYNA provides good predictions of the key variables of structural response during fire. For all benchmarks, it is able to predict the development of temperatures, and development trends of displacements, axial forces, and bending moments with increasing temperature within acceptable level of accuracy if input parameters are carefully chosen.

The use of LS-DYNA for structural fire engineering applications has been demonstrated through application to Arup commercial high-rise building project in London. For the case study presented, the use of LS-DYNA enabled Arup to demonstrate that the structure with optimised fire protection layout can maintain its' stability under a range of severe fires.

5 Literature

[1] Wickstrom, U., and Palsson, J.: “A Scheme for Verification of Computer Codes for Calculating Temperature in Fire Exposed Structures,” SP Swedish National Testing and REsearch Institute, 1999.

[2] Shapiro, A.: “Using LS-DYNA for heat transfer & coupled thermal-stress problems,” Livermore Software Technology Corporation, 2012.

[3] Temple, A., Walker, G., Flint, G., Panev, Y., and Kotsovinos, P.: “Verification of 2D heat transfer models developed in LS-DYNA for structural fire engineering applications,” in *International Conference Applications of Structural Fire Engineering, ASFE'17*, Manchester, 2017.

[4] Gillie, M.: “Analysis of heated structures: nature and modelling benchmarks,” *Fire Safety Journal,* vol. 44, pp. 673-680, 2009.

[5] Zhao, B., Roosefid, M., Vassart, O.: “Full Scale Test of A Steel and Concrete Composite Floor Exposed to ISO Fire,” in *Proceedings of the 5th International Conference on Structures in Fire*, Singapore, 2008.

[6] Rackauskaite, E., Kotsovinos, P., and Rein, G.: “Model Parameter Sensitivity and Benchmarking of the Explicit Dynamic Solver of LS-DYNA for Structural Analysis in Case of Fire,” *Fire Safety Journal,* vol. 90, p. 123:138, 2017.

[7] Law, A., Stern-Gottfried, J., and Butterworth, N.: “A Risk Based Framework for Time Equivalence and Fire Resistance,” *Fire Technology,* vol. 51, no. 4, pp. 771-784, 2014.

[8] Kotsovinos, P., Walker, G., and Deeny, S.: “Reliability based fire severity assessment of modern buildings with open-plan spaces,” in *Conference Proceedings of the 2nd International Conference on Structural Safety under Fire and Blast, CONFAB 2017*, London, 2017.

[9] Rackauskaite, E., Kotsovinos, P., Jeffers, A., and Rein, G.: “Structural Analysis of Multi-Storey Steel Frames Exposed to Travelling Fires and Traditional Design Fires,” *Engineering Structures,* vol. 150, pp. 271-287, 2017.