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Model parameter sensitivity and benchmarking of the explicit dynamic solver of LS-DYNA for structural analysis in case of fire

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ABSTRACT

Due to the complex nature of structural response in fire, computational tools are often necessary for the safe design of structures under fire conditions. In recent years, use of the finite element code LS-DYNA has grown considerably in research and industry for structural fire analysis, but there is no benchmarking of the code available in the fire science literature for such applications. Moreover, due to the quasi-static nature of structural response in fire, the majority of the computational structural fire studies in the literature are based on the use of static solvers. Thus, this paper aims at benchmarking the explicit dynamic solver of LS-DYNA for structural fire analysis against other static numerical codes and experiments. A parameter sensitivity study is carried out to study the effects of various numerical parameters on the convergence to quasi-static solutions. Four canonical problems that encompass a range of thermal and mechanical behaviours in fire are simulated. In addition, two different modelling approaches of composite action between the concrete slab and the steel beams are investigated. In general, the results confirm that when numerical parameters are carefully considered such as to not induce excessive inertia forces in the system, explicit dynamic analyses using LS-DYNA provide good predictions of the key variables of structural response during fire.

1. Introduction

Modern building designs and innovative architectural solutions pose a challenge to structural engineers. This is particularly the case for structural fire engineers due to the complex interactions of modern structural systems in fire. The performance of even generic structures exposed to fire is not straightforward and cannot be easily predicted. As a result, there is often the engineering need to be able to assess structural behaviour under fire conditions from first principles and not rely on blanket prescriptive guidance.

The behaviour of isolated structural elements under standard fire conditions through furnace testing has been extensively studied over the past decade, and can now be predicted with some degree of accuracy using analytical and computational means [1]. However, it has been shown in the past [1–3] that structural fire performance of isolated elements does not resemble the performance of a whole structure. The whole structure performance in a real fire depends on a number of factors. They include restraint, stress redistribution, composite action, and continuity within the structure [4]. The involvement of the many variables makes the analysis and prediction of the fire performance of realistic structures a difficult process. Standard fire tests provide unrealistic results [5]. They do not represent real fire conditions in the compartment and base fire resistance on the performance of the individual elements ignoring the effects of the surrounding structure. Conversely, full-scale testing of real structures is complex, expensive and time consuming. In addition, the limited number of full-scale experiments carried out worldwide (e.g. Cardington tests [5]) has been on buildings of generic rectangular geometry. Thus, they cannot be generalised to predict the performance of all structures, especially where more innovative irregular structural arrangements are used. As a results, designers use computational tools to predict and assess the performance of complex structures under fire conditions.

With increasing computational capabilities, the fire resistance assessment of various structural arrangements under different fire scenarios is becoming more and more used in practice. However, these models have to be benchmarked against experimental data or known solutions to make sure that they produce accurate and physically correct results. Most commonly used numerical models for structural fire analysis include commercial general finite element analysis packages (Ansys, Abaqus) and purpose-based finite element models developed or extended specifically for structural fire analysis (Vulcan,

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SAFIR and OpenSees). All of these models have been widely used for structural fire analysis in the recent years and have been validated against various small-scale and full-scale tests (e.g. Cardington) [6–17].

More recently, researchers and designers [18–20] have adopted LS-DYNA for structural fire analysis. Kilic and Selamet [19], and Selamet [18] used LS-DYNA to investigate the effect of fire location on the collapse of a 49 storey high-rise steel structure. The whole 3D building model was used for the analysis. Law et al. [20] studied the structural response of structural arrangements with bi-linear columns to fire. A slice of the 3D model of a generic substructure was used that included a 4-storey high bi-linear column with adjacent composite beams and concrete slabs. In all of these studies [18–20] the authors used beam and shell elements to represent steel beams and concrete slab respectively. However, neither of them included the benchmarking of the adopted LS-DYNA model. Both et al. [21] published a benchmark for predicting the structural fire response of a centrally loaded steel-concrete column. The column was modelled using solid elements. The results of the coupled thermal-mechanical analysis were presented for ANSYS, LS-DYNA, and ABAQUS. Temperature and displacement development in the column showed a good agreement between those software packages. The maximum differences between the peak values in relation to LS-DYNA results were approximately 23 °C (5%) and 0.23 mm (23%), respectively. Kwaśniewski et al. [22] carried out a coupled thermal-mechanical analysis of a restrained steel column subjected to fire using LS-DYNA and validated against experimental results. The detailed 3D model (as in the benchmark by Both et al. [21]) adopted solid elements.

LS-DYNA is a commercial general purpose finite element software originally developed for highly nonlinear and transient dynamic analysis [23]. It is robust in the analysis of problems involving transient effects, contact and large deformations and has high computational efficiency. As a result, LS-DYNA is one of the most commonly used numerical explicit integration simulation programs. Common applications of LS-DYNA include automotive, aerospace, metalforming, and multi-physics problems. In structural engineering, common applications include earthquake, blast impact, and progressive collapse analysis. LS-DYNA has been used for the aircraft impact and progressive collapse analysis of the World Trade Centre (WTC) towers by NIST [24,25]. However, most likely due to the lack of available scientific work using LS-DYNA, for structural fire response analysis in the same WTC study a different numerical program was used. LS-DYNA as a software has been fully validated and verified by its developers (Livermore) for its generic applications. Even though, in recent years, the explicit dynamic solver of LS-DYNA has grown considerably in research and industry uses for the analysis of structures in fire [18–22], to the best of the authors knowledge, there is still no benchmarking of the code available in the literature specifically with regards to the structural fire performance. Available research is limited to the internal benchmarking work carried out in Arup [26] and detailed 3D solid based individual structural member models [22]. Solid elements are not frequently used for global models or for design purposes. In addition, due to the quasi-static nature of the structural response in fire, the majority of the structural fire analyses available in literature are carried out using static solvers.

Thus, this paper aims at benchmarking the explicit dynamic solver of LS-DYNA for the structural fire analysis of 3D composite structures and 2D steel frames against experiments and other numerical codes. An extensive parameter sensitivity study is carried out to study the effects of various modelling parameters on the kinetic energy and convergence to quasi-static solution. Four canonical problems that encompass a range of thermal and mechanical behaviours in fire are simulated. The term benchmarking is used in this paper to refer to verification and validation of computational models, based on the definitions adopted by the ASTM [27]. That is, evaluating the software for correct application to known benchmark problems and for physical correctness of the results [15,16]. The LS-DYNA model is benchmarked against fire tests on loaded steel framework results [28–30], two benchmarks published by Gillie [31] and results published by Rackauskaite and El-Rimawi [32] on the numerical study of 2D steel frames subject to localised fires.

2. LS-DYNA benchmarking models

For the benchmarking of LS-DYNA for structural fire analysis, we use the double precision LS-DYNA (Release 7.1.1) version. Each benchmarking case chosen for this paper encompasses different mechanisms of structural response in fire, which are required to get a realistic response. In total four benchmark cases are considered. The first benchmark is based on the natural fire test of the 2D steel frame carried out in 1987 [28–30]. It allows the benchmarking of LS-DYNA against experimental results and assessing whether the model correctly captures the effects of non-uniform heating, material non-linearity, restraint, and stress redistribution.

The remaining 3 benchmarks are based on and allow benchmarking of LS-DYNA against the results of numerical analysis published in the literature [31,32]. Gillie [31] has published results for 2 problems which provide benchmark solutions for structural fire analysis. They allow users to check whether their models capture the required phenomena, which occur when structures are heated. The first benchmark [31] is on a uniformly heated steel beam with 75% support stiffness. This benchmark allows to confirm whether the model captures the effects of material non-linearity, geometric non-linearity and restraint conditions [31]. The second benchmark [31] is on a heated composite concrete floor. This benchmark assesses whether phenomena such as stress redistribution, localised heating and composite action effects can be captured. These two benchmarks provide a computational challenge against most of the fundamental mechanisms that occur when structures are heated and, thus, were chosen for the benchmarking of LS-DYNA. In addition to the above, a third benchmark has been chosen based on the study by Rackauskaite and El-Rimawi [32] on the heating effects on a 2D steel frame. In the latter study non-uniform heating of the beams was assumed. Therefore, the adoption of this study as a benchmark allows to assess whether thermal bowing, restraint from the surrounding structure and stress redistribution are appropriately captured in the analysis. In the following sections these benchmarks are described and the results from the LS-DYNA analyses are presented.

2.1. Benchmark #1 (BM1): fire test on a loaded steel framework

Benchmark #1 (BM1) represents a natural fire test on a 2D steel frame carried out in 1987 [28]. The test frame comprised of a 4.55 m long steel beam and two 2.53 m high columns. It was connected to secondary framework to prevent lateral instability. Details of the frame and loading are shown in Fig. 1. This test has already been successfully modelled in CEFICOSS [29], Abaqus and SAFIR [30]. Therefore, a similar modelling approach was used in LS-DYNA for comparative purposes.

Beam web temperature measurement from the test is only available at one instant during the whole fire exposure. Thus, member temperatures, which show a good agreement with the measured test data for beam flanges and column (see Fig. 1), were taken from [29]. The beam was subjected to non-uniform gas temperatures along its length. To account for this, a temperature reduction function following a sinusoidal shape was applied along the beam as in [29,30] with the temperature at the connection being 0.9 of the beam temperature at mid-span. Column temperatures along the height were assumed to be constant.

In LS-DYNA, the steel frame was modelled using Hughes-Liu beam elements with user defined cross-section integration. This element has a single integration point along its length in the middle of the element,