NUMERICAL SIMULATION OF NATURAL FIRE IN AN INDUSTRIAL BUILDING CONSIDERING EARTHQUAKE DAMAGE OF NON-STRUCTURAL MEMBERS

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Abstract
The aim of this paper is to examine the impact of post-earthquake non-structural damages on the development of natural fire in an industrial building, used as storage area. Parametric fire scenarios with various levels of damage (window and door destruction, sprinkler system malfunction) are simulated on a 3D model of the structure, using the Computational Fluid Dynamics software FDS. The fire development is studied and temperature distributions on the structural members are obtained.

Keywords: fire-afterearthquake, steelstructures, natural fire

INTRODUCTION

Post-earthquake non-structural damage can alter significantly the fire behaviour of a building and downgrade the structural safety of the construction. This study examines the impact that such damage has on the development of natural fire, in this case in an industrial building, used as storage area.
The officially approved procedures for estimating the thermal loads for the structural design of industrial facilities under fire require advanced modelling tools for the simulation of the natural fire phenomenon, like the one/two–zone model or the use of Computational Fluid Dynamics (CFD). Simpler approaches such as the parametric temperature-time curves given in Eurocode1,part1-2areonly valid for small compartments, under 500 m^2 and non-industrial occupancies. In this study, CFD analysis is performed with the Fire Dynamics Simulator (FDS) software, to model the fire development in the building. FDS is a CFD code for the simulation of thermally driven flows with an emphasis on smoke and heat transport from fires. The CFD-FDS has two main advantages over the two-zone model: the ability to insert a detailed geometry with a custom-defined burn behaviour of the combustible materials and secondly, the capability of providing time-history temperature results at any position of the modelled structure.

1 MODEL

1.1 Properties of the examined building

The building under examination has a floor plan of 80x40m with a height of 10 m plus a 2m two-ridge roof. The space is divided in two main compartments, the storage area with dimensions 63x40 m and a 2-storey office/exhibition area of 17x40 m with heights 4 and 6 meters respectively (Fig. 1).The storage compartment has a total of 247 m^2 of windows located in a high row on each of the 63m walls. On the ground and first floor of the office/exhibition area are additional 94$m^2$and 58m^2 of windows. In the storage area the supplies are stored in 6.25 m high racks, comprised mainly of electrical appliances and spare parts stored inside cardboard boxes. The structural system of the building consists of seven double-span steel frames. The walls and roof are composed of typical insulation panels. The base is standard industrial concrete flooring. The two compartments communicate through a 5.00x3.00 m fireproof door. Also, there is a water sprinkler system installed in the storage area.

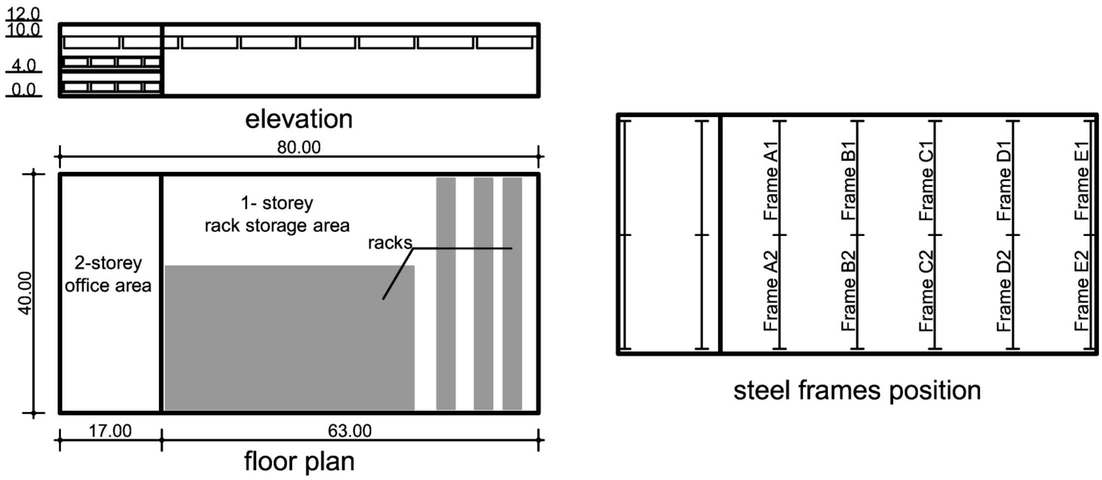

Fig. 1 Building description (dimensions in meters)

1.2 Simulation

A full scale 3D model is developed, representing the basic geometry of the building and the construction materials with their thermal properties (steel, concrete, 10cm XPS insulation). A key parameter of the fire simulation is the description of the combustion behaviour of the materials in the storage area. Due to the complex structure of the burning objects, a pyrolysis model would induce uncertainties in the analysis. To avoid such uncertainties a custom Heat Release Rate (HRR) curve is chosen to represent the combustion. The experiments of A. Lönnermark and H. Ingason on fire spread in warehouses (Lönnermark et al., 2005) provided HRR curves of rack storage fire tests that correspond to the storage conditions in the building under examination. The experiments were conducted in 1:5 scale so the results are modified according to the scaling laws, regarding the HRR and the corresponding time (Fong et al, 2003).

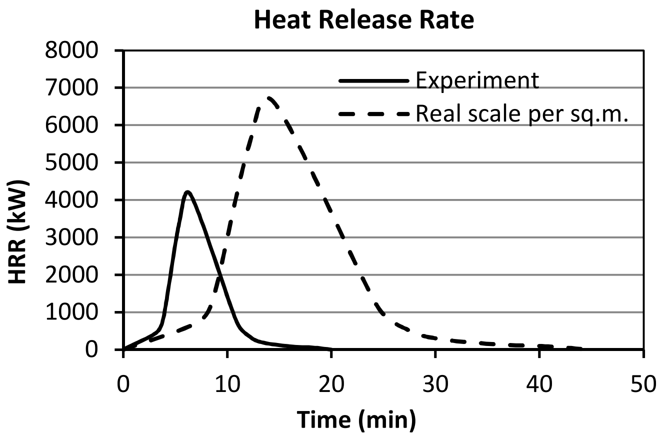

Fig. 2 Experiment and modified real scale Heat Release Rate curve of the rack storage units

The storage racks, are modelled by 156 heat release sections in parallel rows, at a distance of 1.20m, covering the designated area in the floor plan. In order to simulate the fire spread from one rack unit to another, a criterion of the temperature conditions that would ignite the

materials is used. Each heat release section is activated only when the temperature over the section reaches 250°C, the auto ignition temperature of wood (Babrauskas, 2002) and paper (Graf, 1949). This concept is implemented by connecting the activation of each heat release section to a temperature sensor 3m above the centre of the section. This results in a more gradual activation of the heat release sections, dependent on the temperatures of the compartment. It is assumed that the fire does not spread through flames but through radiation and convection flux that starts the pyrolysis of the cellulose materials which produces the combustible gases. A required condition for the combustion to occur is an oxygen index >0.15. If this is not satisfied the fire is suppressed.
The computational mesh consists of 225,000 cells of 0.80x0.80x0.60 m and extends 10 m around and 3m above the building with open boundaries at the end. As ignition of the fire, two of the heat release units in the middle of the compartment are set active in the beginning of the simulation, in order to provide the equivalent amount of heat that was observed at the experiment. The total simulation time is 1 hour and the calculation time steps are set not to exceed 0.1 sec.

1.3 Parametric Fire Scenarios

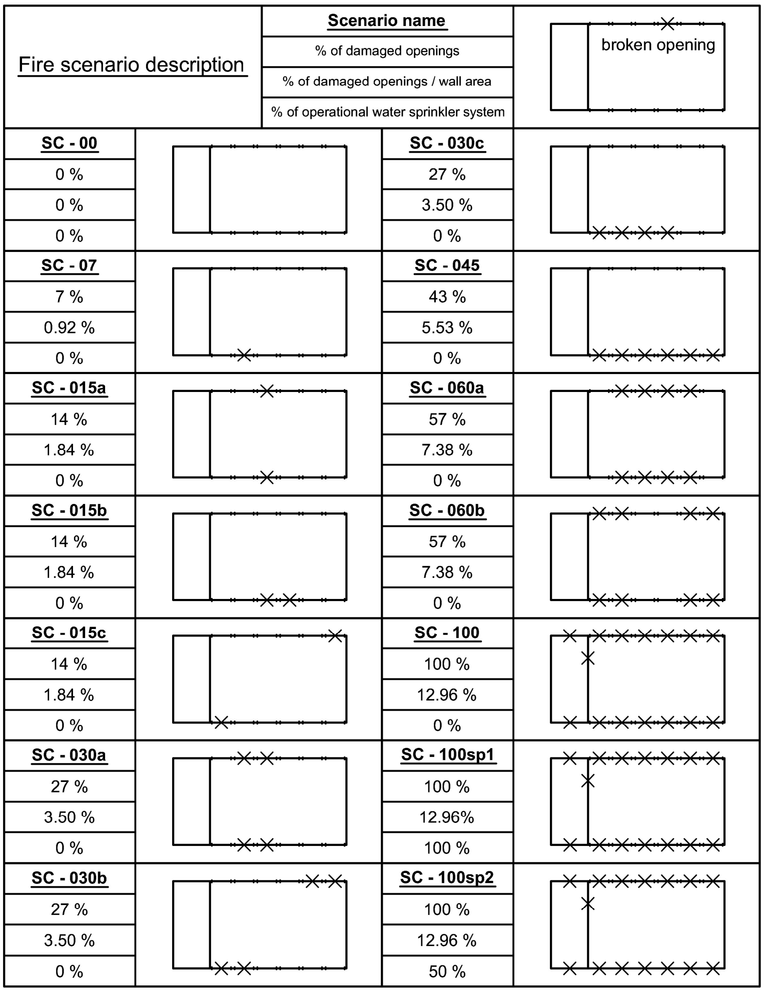

Fig. 3 Parametric Fire Scenarios

Three types of non-structural “damage” were introduced to the model:

- window breakage, which modifies ventilation conditions,
- fireproof door damage which modifies ventilation and alters the fire compartment
- malfunction of the water sprinkler system.

In total, 14 fire scenarios were tested. Of those, 12 included variations in the ventilation conditions by changing the number and placement of the broken windows and damage of the fireproof door. The remaining 2 had full and half operational the water sprinkler system. A visual description of the scenarios is given in Fig. 3. For every scenario, the following parameters are given: percentage of broken openings to the total area of openings in the storage compartment, percentage of the broken openings to the total wall area, position of the broken openings and percentage of the operational water sprinkler system.

2 OUTPUT RESULTS

Tab. 1 Duration (min) of temperature exceeding 600°C on the steel frames for every scenario

Duration over 600 °C		Frames										AVERAGE (min)	ST.DEV. (min)
		A1	A2	B1	B2	C1	C2	D1	D2	E1	E2		
Fire scenarios	SC-00	0	2	4	2	0	3	0	0	0	0	**1**	**1.4**
	SC-08	8	2	4	4	0	2	0	0	0	0	**2**	**2.7**
	SC-015a	7	2	12	7	6	2	0	0	0	0	**4**	**4.0**
	SC-015b	2	4	3	14	2	4	0	0	0	0	**3**	**4.0**
	SC-015c	5	8	5	5	0	2	6	0	17	0	**5**	**5.0**
	SC-030a	30	20	44	36	29	26	10	9	6	4	**21**	**13.1**
	SC-030b	8	28	7	20	18	4	40	12	41	20	**20**	**12.4**
	SC-030c	8	30	10	36	6	19	3	5	0	3	**12**	**11.6**
	SC-045	13	28	15	38	14	38	7	37	13	32	**23**	**11.6**
	SC-060a	42	37	46	44	42	41	38	38	35	26	**39**	**5.3**
	SC-060b	43	46	42	40	37	33	37	39	37	38	**39**	**3.4**
	SC-100	20	23	21	36	17	23	15	18	15	16	**20**	**6.0**
	SC-100sp1	0	0	0	0	0	0	0	0	0	0	**0**	**0.0**
	SC-100sp2	**0**	0	0	5	0	0	0	0	0	0	**1**	**1.7**

Tab. 2 Average duration (min) and st. deviation of temperature levels on the steel frames

Duration over (minutes)		600 °C		700 °C		800 °C		900 °C		1000 °C	
		average	st. dev.	average	st. dev.	average	st. dev.	average	st. dev.	average	st. dev.
Fire scenarios	SC-00	1.1	1.4	0.2	0.6	0.2	0.6	0.2	0.6	0.2	0.5
	SC-08	2.1	2.7	0.7	1.1	0.2	0.6	0.2	0.7	0.2	0.5
	SC-015a	3.6	4.0	1.5	2.7	0.8	1.8	0.2	0.7	0.2	0.7
	SC-015b	2.9	4.0	1.7	2.4	0.9	1.9	1.2	2.3	0.8	1.7
	SC-015c	4.9	5.0	1.9	3.4	2.0	4.1	0.8	1.4	0.5	0.9
	SC-030a	21.3	13.1	8.2	10.0	3.3	5.7	1.9	4.1	1.6	3.4
	SC-030b	19.8	12.4	8.2	8.8	5.1	7.5	3.8	6.8	2.0	4.4
	SC-030c	11.9	11.6	4.1	4.1	1.9	2.0	1.3	1.6	1.0	1.2
	SC-045	23.4	11.6	8.4	5.9	4.5	3.1	3.1	2.3	2.0	1.7
	SC-060a	38.9	5.3	23.2	12.2	11.8	9.7	8.3	7.0	6.2	6.7
	SC-060b	39.3	3.4	22.8	10.1	11.9	6.9	9.4	6.3	6.8	5.9
	SC-100	20.4	6.0	17.8	4.9	15.9	3.9	12.0	4.9	6.6	3.4
	SC-100sp1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	SC-100sp2	0.53	1.66	0.39	1.24	0.39	1.24	0.38	1.09	0.14	0.44

Temperature time-histories of the members of the 10 steel sub-frames of the storage compartment which was mainly affected by the fire, are obtained for each fire scenario. The time histories of the frames are difficult to be compared. Instead, the total time that every frame was subjected to temperatures over 600°C (Table 1), 700°C, 800°C, 900°C and 1000°C is summarized. Due to the non-uniformity of the ventilation and fire development, a number of frames are affected at a different level for every scenario. To include both the degree and spatial extent of the thermal impact on the overall structural system, the average time and standard deviation of the exposure of the frames is computed for every temperature level (Table 2). Among the scenarios with the highest average, the most severe is determined by the smallest standard deviation which indicates that more of the frames are affected by the fire and contribute to the average temperature duration. Also the total HRR curves of the fire scenarios are presented in Fig. 4.

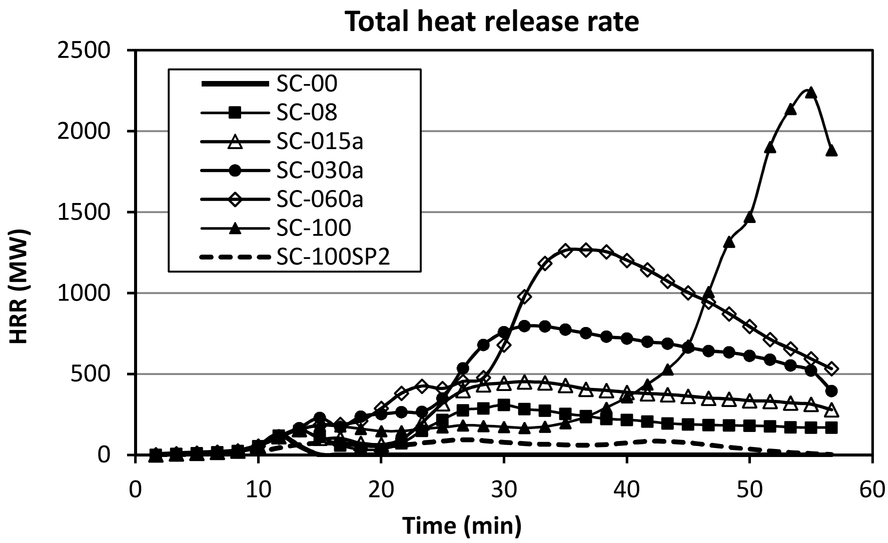

Fig. 4 Total heat release rate for the considered fire scenarios

3 DISCUSSION

For the temperature level of 600°C (Table 1) and 700°C(Table2) the thermal exposure of the steel frames rises as the number of broken windows increases, but reaches a maximum for 60% window damage in scenario SC-060b. As expected, open windows provide fresh air to the fire after the oxygen within the compartment is consumed. Therefore, after some time, the combustion takes place in the vicinity of the openings and affects stronger the nearby frames. As a result, the arrangement of the open windows can lead to a more contained or spatially extended fire (scenarios SC-030a/b/c and SC-060a/b). The scenarios SC-030a/b/c have the same degree of total damage, about 30%, but the position of the broken windows differs. In scenario SC-030a the broken windows concentrate on the right side of the floor plan, in SC-030b are placed diagonally on the opposite walls and in SC-030c only on one side. In Table 1, were the 600°C level is presented on the sub-frames in more detail, it is evident that the damaged windows determine which sub-frames are more affected by the fire. In SC-030a the frames A,B,C are mostly affected, in scenario SC-030b all the frames are affected, especially the ones closer to the openings, and in scenario SC-030c it is clear that the sub-frames A2,B2,C2,D2, placed on the side of the open windows, are the most exposed to heat. The same effect is observed in scenarios SC-015a/b/c, where in scenario SC-015c (with the windows placed diagonally) the most affected frames are the ones next to the windows(frames A2 and E1). Also, the longer distance between the combustion positions (the location of the open windows) generates air flow that spreads in the whole compartment and produces further combustion.

The decrease in the heat exposure that is observed for the temperature level of 600°C for the scenario with all the openings damaged (SC-100), is a result of the slower fire development that has a very steep growth rate after 45 minutes in the simulation (Fig. 4). This situation leads to higher temperatures with smaller duration and is evident in the higher temperature levels of 800°C, 900°C and 1000°C (Table 2). In these temperature levels the scenario with all the windows broken (SC-100) appears to be the most detrimental, regarding the total thermal exposure. However, the fact that this fire has a significantly slower growth rate, which escalates after 40 minutes in the simulation, provides a better chance of being extinguished by conventional means and the fire-fighting crew. This is probably a result of the air flow that brings colder fresh air in the compartment from the beginning of the simulation and disperses the released heat from the burning racks, increasing the time it takes for the temperature to reach 250°C and activate the rest of the heat release sections. Thus, if the fire is extinguished manually within 40minutes, the SC-060 leads to higher fire loads. The 100% window damage scenario SC-100 is critical only if the fire is allowed to fully develop and its duration exceeds 1 hour.

Regarding the operation of the sprinkler system, even partially functional can result in the suppression or restriction of the fire, but that highly depends on whether the functional part covers the fire ignition point. The total damage of the sprinkler system is the main reason that extended fire occurs in the compartment so designing a sprinkler system that can withstand seismic displacements is a key factor to the fire design of an industrial facility.

The fire development depends highly on the air supply in the compartment and can even be self-suppressed if there is no ventilation at all (SC-00). A change in the ventilation conditions can be a result of non-structural damage that is most likely to occur during an earthquake. In this case, a fire in addition to a non-functional fire-extinguishing system, can lead to temperatures of magnitude more than 1000°C which are not expected to arise during the fire design process, where the various systems are considered undamaged and fully functional.

4 CONCLUSIONS

Post-earthquake non-structural damage influences greatly the development of natural fire in an industrial building, especially when combustible materials are in abundance. Although fire loads are not combined in the design with earthquake loads, post-earthquake fire is a probable event and post-earthquake non-structural damage has to be taken into account in the fire design process.

The most influential damage is the malfunction of the active fire protection systems, which are not necessarily designed to withstand seismic forces and displacements. A revision of the design of such systems considering earthquake performance is advised.

Window damage causes change in the ventilation conditions and could lead to temperatures different than the ones considered in the design process. As a result, it is recommended that the fire retardant coating of the steel members should be adequate for the temperature time-histories produced by fire not suppressed by an extinguishing system.

The CFD analysis is a useful tool that can aid the fire design of buildings which do not conform to the provisions for a simpler design approach, though it should be used with caution, as is the case for all advanced computational methods.

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