RISK ANALYSIS BASED STRUCTURAL DESIGN FOR FIRE SAFETY

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1. ABSTRACT

The problem of structural fire safety in the recent years has gained a predominant position within the engineering design, with the affirmation of Performance Based structural Codes and Standards, replacing more and more the traditional Prescriptive Based ones. This is because nowadays, structures always bigger and more complex are designed and build, with the use of particularly fire sensitive materials. In modeling such complex structures, there are important aspects that need to be taken into account, especially when setting the boundary conditions of the structural problem as defined by the design environment.

In this paper, aspects of the fire risk analysis procedure applied in an industrial facility are presented, along with the numerical modeling of the consequent structural behavior. The aim is to evaluate by means of nonlinear non stationary analyses what happens to the structural elements, and as a consequence to the structure, when the fire is not restrained.

2. INTRODUCTION

The use of analysis with thermo-plastic material and with geometric nonlinearity and the modeling of fire action by using of parametric curves allow the correct evaluation of the real behavior of steel structures subject to fire.

In this context, once these two basic aspects have been understood, they are developed in steel structures subject to fire action. For these structures the collapse can be quantified when they are subject to localized fire, modeled using a parametric curve. The evaluation of the structural collapse is very tricky and depends from many aspects; in particular, in a Performance Based approach that even is used for buildings subject to fire, it is important to consider the global vision of the structure itself. The prescriptions derived by the exploitation of the Fire Safety Engineering, come as an aid to the above.

3. FIRE SAFETY ENGINEERING

Although at present there is no internationally agreed definition of Fire safety Engineering (FSE), FSE can be defined as the application of engineering principles, rules and expert judgment based on a scientific understanding of the fire phenomena, of the effects of fire, and of the reaction and behavior of people, in order to:

- save life, protect property and preserve the environment and heritage;
- quantify the hazards and risk of fire and its effects; and
- evaluate analytically the optimum protective and preventative measures necessary to limit, within prescribed levels, the consequences of fire.

In the above sense, becomes important the performance evaluation of the structure. In particular, within the FSE approach, two concepts have found application:

- The Performance Based Fire Safety Design (PBFSD) of the structure.
- The Fire Risk Assessment (FRA) of the structure.

As the name suggests, Performance Based Design in general, is a design that meets a specified performance level rather than prescribe specific design criteria. The performance approach for the design of structures begun to be diffuse in the last sixty years, mostly for facilities with elevated risk of fire. This kind of Performance Based approach, has been applied in other circumstances, particularly for seismic design. A performance-based fire safety design starts with an analysis of fire scenarios, in order to determine which design alternatives will meet those fire safety goals. These goals are either referred to the structural performance or to the performance of the system in general. In the first case, the focus is on the structural performance in the presence of fire and includes requirements of fire resistance for the structural elements (e.g. beams, slabs, columns) or for the structural system as a whole (avoidance of excessive vibrations, of progressive collapse, etc.). A very important step to guarantee a determinate level of safety is to verify that the resistance of the structure under fire is higher than the fire severity (fire resistance > fire severity). There are three technique of check for the fire resistance (in the time, temperature or resistance domain), as explained among all in the Italian Building Code [1].

The FRA of the structure, is an incorporated part of the PBFSD, and is codified in many Standards [2,3]. One of the aims of the Standards is to provide the methodology on how to evaluate the scenarios to be considered for further analysis, by means of standard methods of Risk Analysis (e.g. qualitative, quantitative, probabilistic etc.).

A framework is set by [4], which provides the following key aspects of the risk ranking process:

- identification of a comprehensive set of possible fire scenarios;
- estimation of probability of occurrence of the scenario;
- estimation of the consequence of the scenario;
- estimation of the risk of the scenarios (reflecting consequence and probability of occurrence);
- ranking of the fire scenarios according to their risk.

By using the above prescriptions, it is possible to perform the fire risk assessment of a complex structural system, such as the one considered in the following paragraph.

4. FIRE RISK ASSESMENT OF A COMPLEX STRUCTURAL SYSTEM

The structure under inquiry is an industrial facility in steel, used for the storage and maintenance of helicopters, therefore it presents with an elevated fire risk. The facility is 64.64 meters long, 32.85 meters wide and has a maximum height of 12.9 meters as shown in Figure 1.

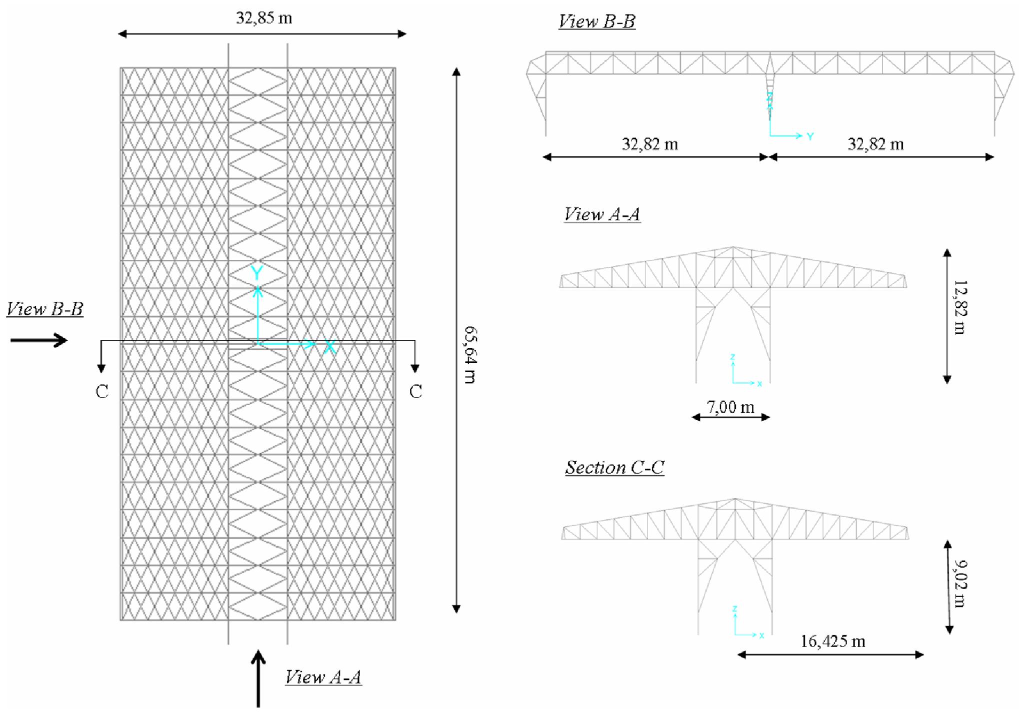

Fig. 1: Geometry of the facility

The triggering event considered is the fire ignition on a helicopter. In this case, fire ignition sites are identified on the basis of the most adverse locations (that could have the most severe affect on the structural performance of the facility). The above scenarios are identified by carrying out a risk-analysis procedure (her omitted for the sake of brevity), considering cause-consequence diagrams as the one shown in Figure 2 for the most prone to risk zones of the facility.

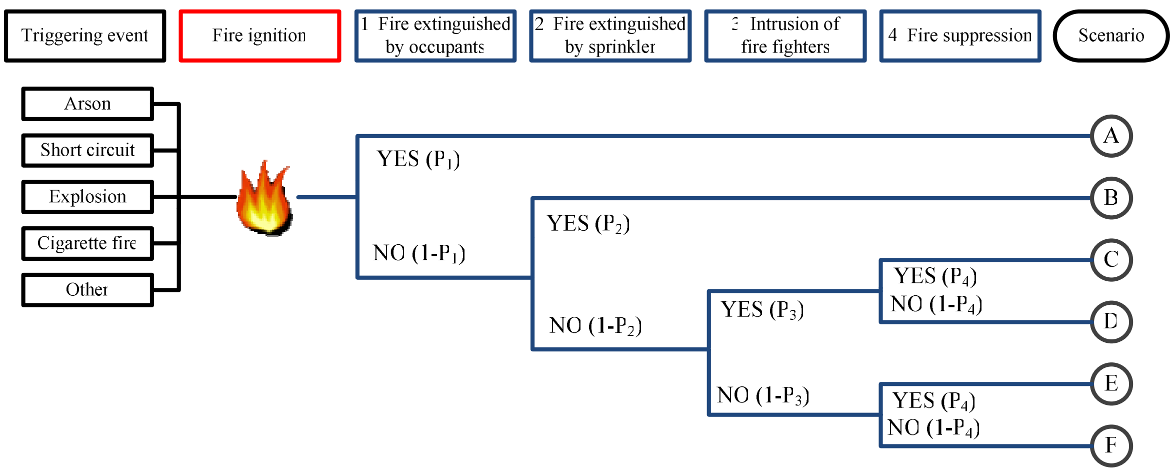

Fig. 2: Cause-consequence diagram for fire risk in one area of the facility

This facility presents a relatively complex geometry. The structure is isolated, it presents symmetry both in the *x* and in the *y* direction and it has a truss covering. There are six vertical elements, composed by a block of concrete at the end of these, start steel elements, those composes the column.
To assess the safety of this structure in case of fire, in this case, the performance level that does not contemplate collapse for all the duration of fire, has to be guaranteed. As a consequence, a check in order to evaluate the fire resistance is done, by modeling the fire action by means of the nominal standard curve provided by [5]. This curve has been applied only to the elements directly involved to the fire action.
To value the fire resistance of this particular structure, three fire scenarios are considered. These three scenarios are localized in zone of about 50 m^2, that is about the 2,5% of all surface of building.
It is important to remember that a localized fire is a fire that interests a limited area of the whole structure, in which, the release of heat, remains concentrated in the area itself.
The choice of important fire scenarios for the case studied is fell on the individuation of three zones, shown in Figure 3:

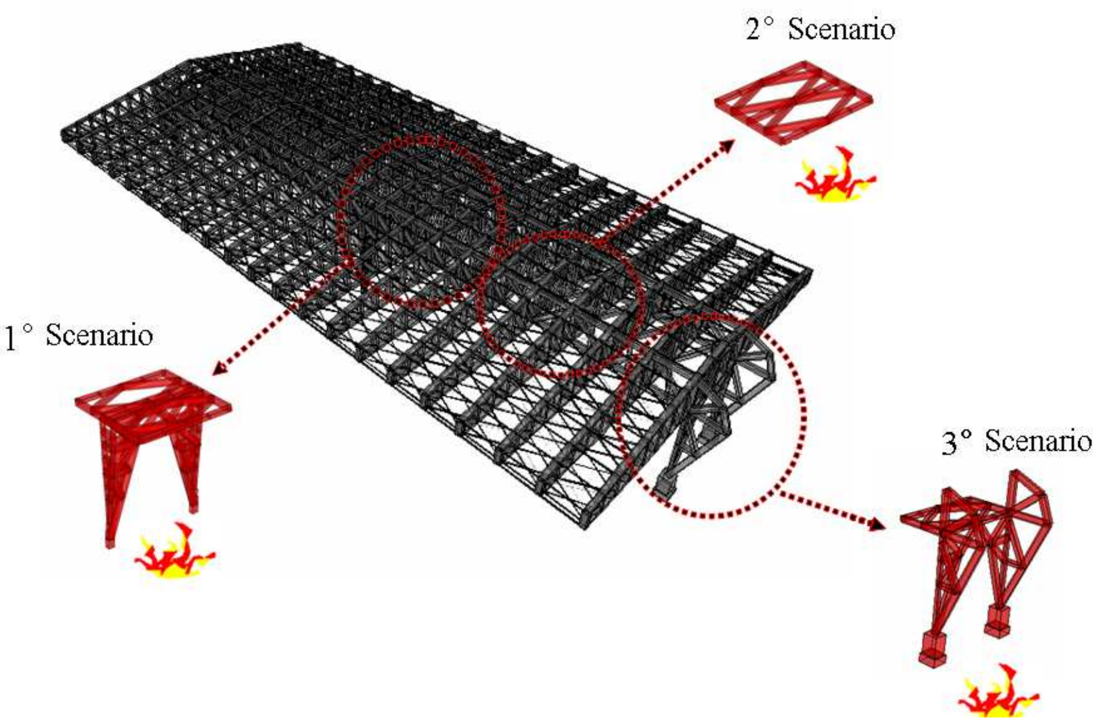

Fig. 3: Fire scenarios chosen.

1. In the first scenario the fire is concentrated in the central zone of building, involving also the central columns.
2. In the second scenario the fire is localized in the central zone of the span without involving any columns.
3. In the third scenario the fire is localized in the outer zone, involving also the column of the outer side.

It is very important to highlight the importance of the choice of the scenarios; in fact, should they not correctly depict the reality, the “Performance-Based” Design of the structure could be compromised.
The analyses performed, implemented in a commercial code (www.adina.com) account for the material and geometry nonlinearities, thus being able to accurately describe the actual behavior of the structure. This involves a large engagement in terms of time and memory

on the computer: for example, for the model of this application with 1205 nodes, corresponding to 7230 degrees of freedom, the analysis lasts for five hours with a normal processor. Particular attention is given also to the static scheme of this structure, composed by a reticular covering and it is so very redundant, as shown in Figure 4.

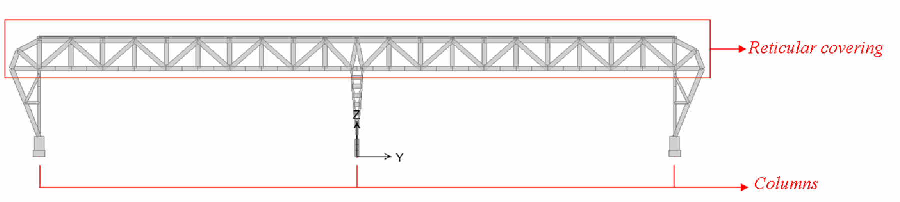

Fig. 4: Identification of structural element of the building, view B-B

Some considerations are necessary on the front of the structural dependability of the facility [6], in terms of collapse resistance [7]. If a structure is redundant, then there are many alternative load paths, large deformations can develop without a loss of its load bearing capacity, and structural failure must be accounted for in a different way. This phenomenon creates sufficient reserve capacity to allow most of such structures to survive fires with little structural damage. For the above reason, it is important to make some considerations about the facets of structural collapse.
It is possible to verify that the collapse of a single metal bar, although of a certain significance, doesn't compromise the global behavior of the whole structure. Therefore, the local collapse of a single (or a limited number) of the covering bars has to be dealt with differently compared to the collapse (or loss of resistance) of the vertical elements (columns) which do not offer redundancy in this building. The collapse can be evaluated as a function of the global behavior of the whole structure, assigning particular importance to the more resistant elements, and after that, to the columns.
The trend of the node displacement corresponding to the columns affected by the fire are reported referring to the 1st scenario (Figure 5).
For this first scenario, the trend of the node n°5438 of the central column is evaluated.

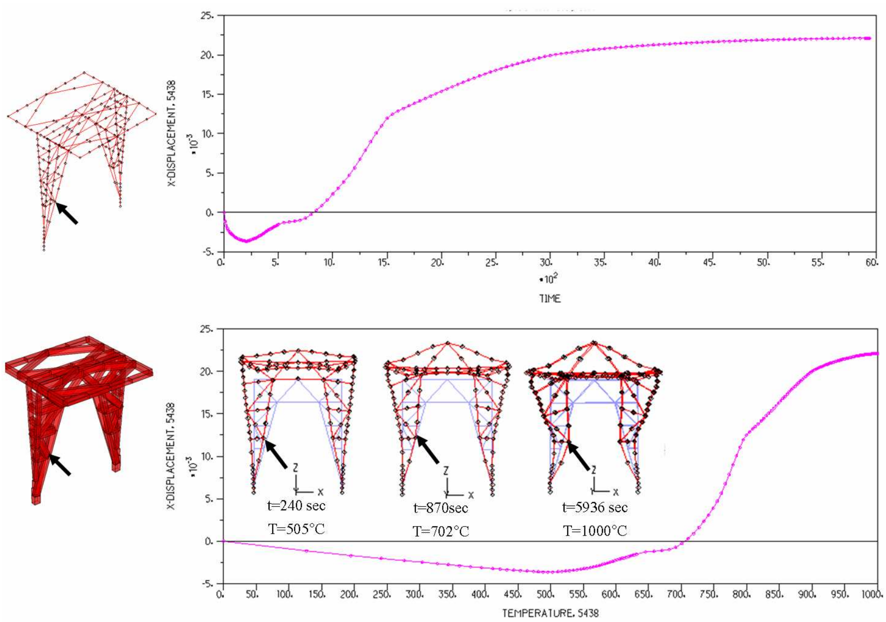

Fig. 5: Displacements of node n°5438 of the column along the x axis (scenario n°1)

For this trend a point of discontinuity seems easily to single out.
In fact, after 800 seconds, which corresponds to a temperature of approximately 700°C, the trend of displacements of the *x* axis of the node n°5438 goes through negative values, for the effect of temperature that initially produces large thermal expansion, to positive values.
This passage is due to loss of stiffness and resistance produced by the elevated temperature, in this way the element starts to skid towards the weakest direction. From what said, it is not possible to suggest that after 13 minutes the structure collapses, but it is reasonable to think that over this time limit, the column suffers a modification of stiffness and resistance that, in a Performance Based approach, highlights the possibility that the safety of the structure cannot be guaranteed.
Similar considerations stand for the third scenario, considering the displacements of the node n°5438 and n°5436 of the extreme columns subject to fire (the graphs are omitted for the sake of brevity).
In Figure 6 the deformed configuration along the *x* and *y* axis, referring to the 1st and 3rd scenario are shown, an in Figure 7, the deformed configurations on the BB plane.

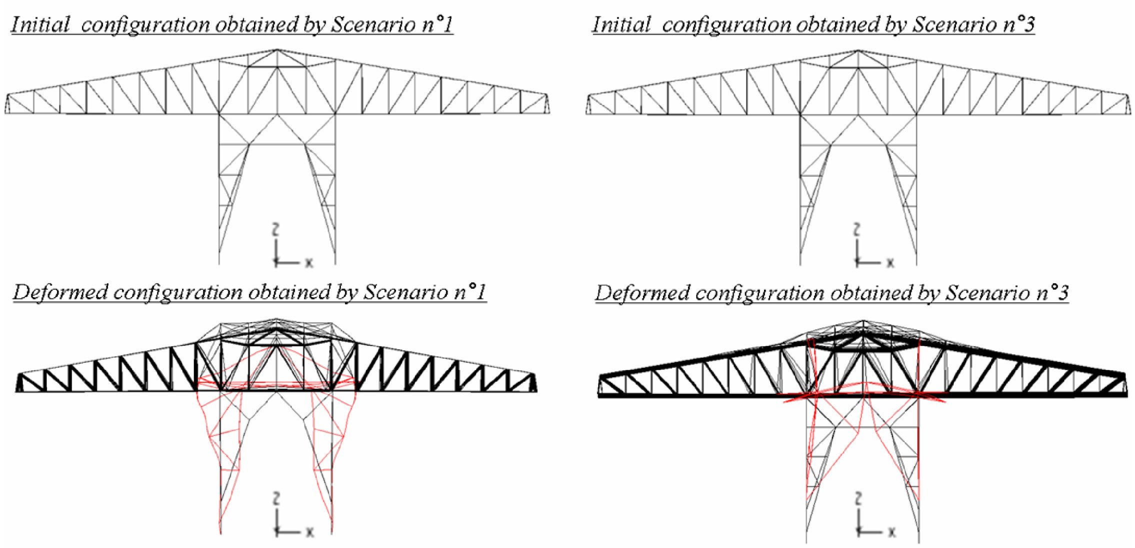

Fig. 6: Deformed configurations over the x and y axis of the 1st and 3rd scenario, view A-A

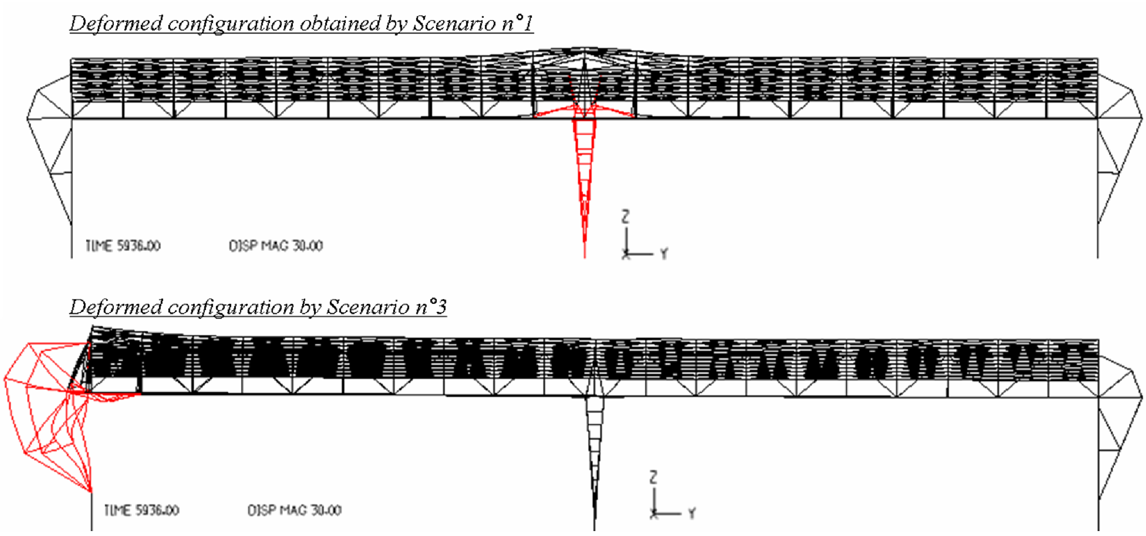

Fig. 7: Compared configurations of the three scenarios considered, view B-B.

The results referring to the 2nd scenario are omitted since this scenario doesn’t involve the columns, therefore, for what said before, it doesn’t lead to structural collapse.
From the evaluation of other nodes in the 3rd scenario, specific points of discontinuity are pointed out. These points do not correspond to the collapse of the structure but they show that in excess of them, the upholding of the performance level may not be guaranteed.
From these consideration it is possible to conclude that for the scenarios involving the columns, after 800 seconds, corresponding to a temperature of 700°C, the structure shows an abrupt change in stiffness, and therefore, this temperature represents a critical state that can make this structure less safe regarding to its stability.

5. CONCLUSIONS

In this paper, the performance of a complex structure under fire is assessed. To this aim, the application of nonlinear analysis on the thermo-mechanic behavior of materials and on structure as a whole, together with the appropriate fire modeling in pragmatic scenarios, consents to:

- demonstrate and verify the performance of the structure in terms of resistance to fire during the design phase;
- identify in a proper way, the operations necessary to obtain the expected performance requirements during the retrofitting phase; this practice, coherent with the Performance-Based Design philosophy, allows to avoid extensive procedures, often uselessly expensive and, sometimes, illusory of safety [8].

The effective behavior of steel structures subject to fire is rather complex, and therefore, their evaluation must to be assessed considering the global behavior of the structure. Furthermore, the definition of collapse of a structure is connected to many aspects: among all, very important are those related to the structural and thermal modeling of the problem under examination. What said indicates that only with non linear non stationary analysis is possible to obtain realistic numeric results.

6. REFERENCES

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ΠΕΡΙΛΗΨΗ

Το πρόβλημα της πυρασφάλεια των κατασκευών τα τελευταία χρόνια, έχει λάβει ισχύουσα θέση στον τομέα του στατικού και δυναμικού σχεδιασμού, με την καθιέρωση κανονισμών αξιολόγησης των κατασκευών βάσει επιθυμητών στόχων συμπεριφοράς, οι οποίοι αντικαθιστούν με σταθερά βήματα τους παραδοσιακούς περιγραφικούς κανονισμούς. Αυτό διότι, τη σήμερον ημέρα, σχεδιάζονται και κατασκευάζονται δομικά συστήματα μεγαλύτερα και όλο και πιο σύνθετα, κάνωντας χρήση ιδιεταίρως ευαίσθητων στην φωτιά υλικών. Κατά την προσομοίωση τέτοιων σύνθετων κατασκευών, υπάρχουν σημαντικές πτυχές που χρειάζονται να ληφθούν υπ'όψιν, ειδικά κατά τον ορισμό των οριακών συνθηκών του εξαρτομένου από τον περιβάλλοντα χώρο στατικού και δυναμικού προβλήματος.
Στο άρθρο αυτό, παρουσιάζεται μέρος της διαδικασίας ανάλυσης ρίσκου προερχομένου απο πυρκαγιά σε ένα βιομηχανικό κτήριο, μαζί με την απορρέουσα αριθμητική προσομοίωση της δυναμικής ανελαστικής συμπεριφοράς του δομικού συστήματος. Ο στόχος είναι η εκτίμηση της συμπεριφοράς του δομικού συστήματος κατά την αύξηση της θερμοκρασίας, ως επακόλουθο της εξάπλωσης της φωτιάς.