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FIRE DESIGN STUDY CASE OF A HIGH-RISE STEEL STORAGE BUILDING

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ABSTRACT

This paper presents a fire design study case for a high-rise storage rack supporting building. Standardised ISO and natural fire models were considered for the fire action. The structural analysis was carried out by means of the advanced numerical program SAFIR, an FEM software specialised for the thermal and mechanical analysis of structures submitted to the fire.

Key Words: *Fire Design, Steel Storage Building, Natural Fire, FEM analysis*

1. INTRODUCTION

From the legal point of view, the classic rack systems included in a building with an independent resistance structure are usually not supposed to have an imposed fire resistance. These racks are considered only in order to evaluate the fire load density provided by the stored goods. More and more yet, high-rise rack supported building systems are constructed, as shown in Figure 1, in which the pallet racks are used to support the roof and walls of the building. For this type of warehouses, the racks become the resistance structure, so they have to be verified in case of fire.

The structure considered in the present study [1][2] is a steel storage building from the Belgian company TRAVHYDRO. The warehouse, operated by automatic systems, is built in France at Amiens for Procter & Gamble Company, and has a surface of $9168m^2$ for 30m high. There are 36 racks on the 160m length of the warehouse. Between the cross-aisle frames of the racks, horizontal elements are provided, in order to maintain the distance between the rails for the wagons of the automatic pallet transport system. A detail of the cross-aisle direction of the building is presented in Figure 2. On the down-aisle direction, one rack has 60m length and is provided with 10 levels for pallet disposal, as Figure 3 suggests.

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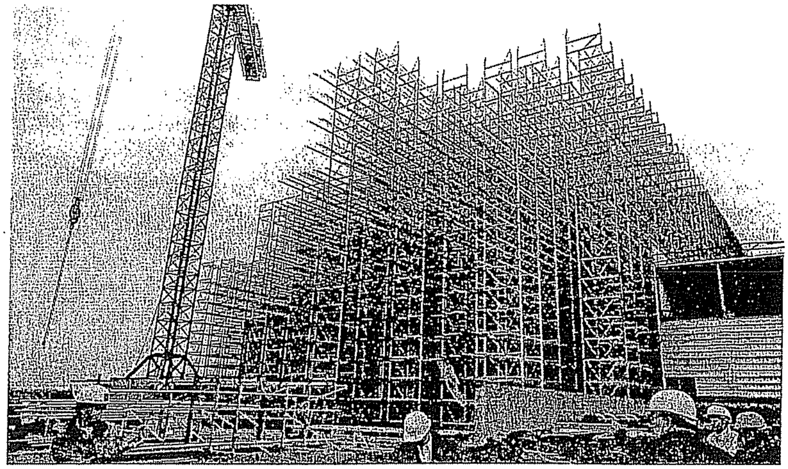

Fig. 1. Rack supported building storage system

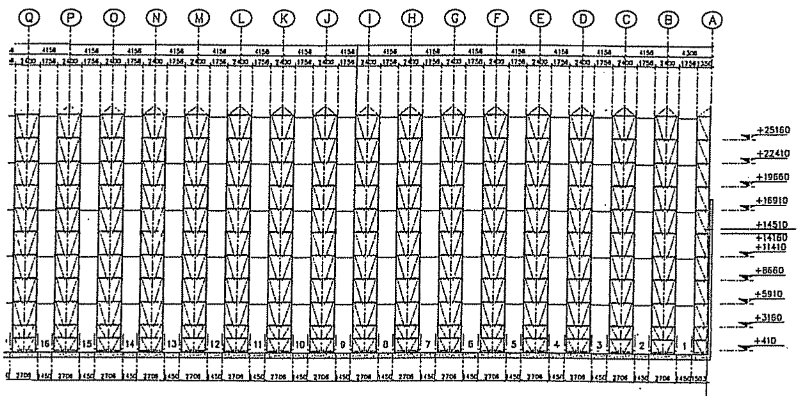

Fig. 2. Cross - aisle direction

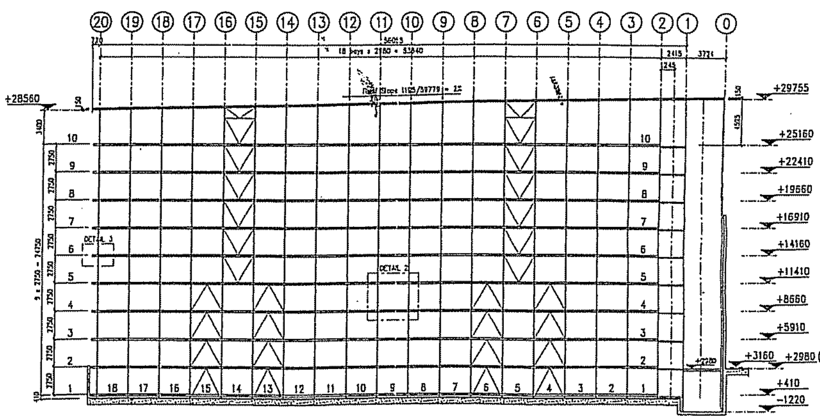

Fig. 3. Down-aisle direction

Normally, for this type of industrial building, and accounting for the existence of the sprinkler system, a fire resistance time of 15 minutes is required. A special requirement for this building, in the hypothesis of a malfunction of the sprinkler system, was that the firemen may visit the building on their arrival, without danger. That means that, even if one rack of the structure falls down, the entire building must not present a progressive collapse phenomenon. Concerning the safety of the existing persons in the building, it must be emphasised that only 2 people are authorised to enter the building, for two hours, once a week. These people are trained for fire situations, know the building, and they may evacuate in less than 10 minutes from the moment of fire discovery.

2. FIRE MODELS

The fire development and extension in a compartment in the first phase are influenced by the active protection measures (as detection or automatic extinction). The fire intensity and development after the flashover phase is conditioned by several causes, from which the most important are the fire load density, the type of fire spread and the ventilation. There are several fire models, accepted by the actual European standard for fire design [3].

The nominal ISO time-temperature curve, accepted by almost all of the fire standards, does not take into account any physical parameter, and can be far away from reality. From the beginning, the nominal model supposes that the entire compartment is in the flashover phase and the temperature is increased continuously, without taking into account the cooling phase.

A modern fire model approach is the combined `Two Zone` and `One Zone` model, which is introduced in the latest proposal of the EUROCODE 1 [4]. In this model, in the pre-flashover phase, the fire compartment is divided in a hot upper zone and a cold inferior one, separed by a virtual membrane. For each zone, with uniform temperature, mass and energy equations are solved. Complex equations describe the air movement in the fire plume, the radiative exchanges between the zones and the gas movements on the openings and adjacent compartments. After the flashover, the temperature in the compartment is considered as uniform and is determined by solving the equations of mass and energy of the compartment, taking into account the walls and openings. This model leads to complex calculations and therefore a computer program is needed in order to solve the equations of the system.

In the frame of the ECSC research "Natural Fire Safety Concept" [5] it was considered necessary to develop a computer program for this model. Being part of the Working Group I "Natural Fire Models", the Department M&S from the University of Liege, took this in charge through the fire research team conducted by the second author. This objective is now reached, a computer program called ***OZone*** is available in order to determine the temperature-time curve by means of the `Two Zone` and `One Zone` concept. This program was validated through different fire tests and gives good results.

3. ANALYSIS OF THE STRUCTURE UNDER ELEVATED TEMPERATURES

The mechanical analysis of the Procter & Gamble warehouse was realised with the SAFIR computer program [6]. SAFIR is a special purpose program for the analysis of structures under ambient and elevated temperature conditions. The program, developed at the University of Liege, is based on the Finite Element Method.

The analysis of a structure exposed to a defined fire consists of several steps. The first step involves the prediction of the temperature distribution inside the structural members, referred to as 'thermal analysis'. Figure 4, for example, shows the temperature distribution in the cross section of rack upright after 10 minutes of ISO fire, taking into account the radiation in the internal cavity formed by this tube. The second step of the analysis, termed the 'structural analysis' is carried out for the main purpose of determining the response of the structure due to static and thermal loading.

3.1. Mechanical analysis under ISO fire

In the standardised ISO fire, the entire compartment is in the flashover phase. Taking into account that there are no separating walls for the entire length of 160 m of the Procter & Gamble storage building, the fire compartment in this case is the interior of the building itself, in which the temperature is supposed to be uniform.

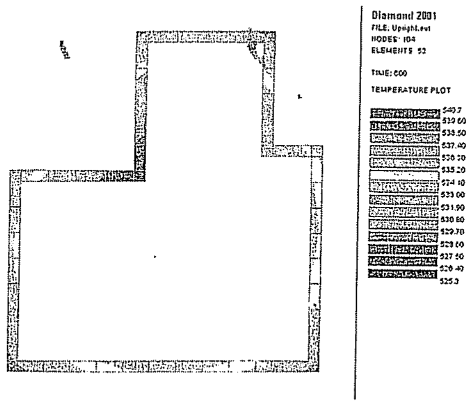

Fig. 4. Temperature distribution for upright cross-section

3.1.1. Cross - aisle direction

As it may be noticed in Figure 5, as the temperature increases, the horizontal elements between the cross – aisle frames exhibit buckling due to restraint and they are progressively suppressed from the analysis. Thus, groups of frames appear, which are pushed from one side by the horizontal elements, which are expanding. The buckling resistance of the horizontal elements as a function of temperature was computed according to the simple method of EUROCODE 3 Part 1.2 [7].

Considering the forces pushing from one side of the frame, after the buckling of the horizontal elements from the other side, the ISO fire resistance is of only 2'47".

A solution to obtain better resistance time is to cut the continuity made by the horizontal elements and the traverses of cross-aisle frames, on the 160 m length of the building. This can be produced, by realising the bolted connections between traverse and upright with slotted holes on the five traverses corresponding to the horizontal elements. Considering this solution, no more buckling of horizontal elements appears, and the resistance time of the cross-aisle frames is of 5'. In order to have smaller displacements due to thermal elongation, a solution may be to replace the steel horizontal elements by timber elements of the same resistance. In this way, 6'42" of fire resistance are obtained.

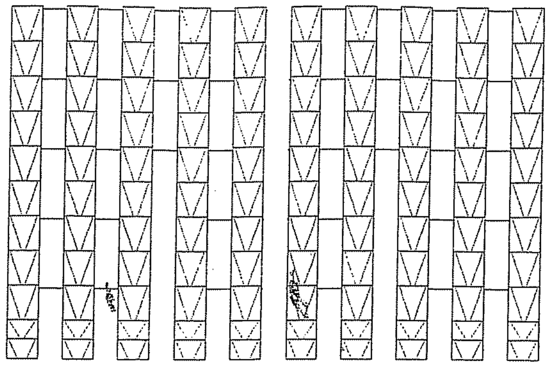

Fig. 5. Cross-aisle frames interaction

3.1.2. Down - aisle direction

For the down-aisle direction, the buckling of the first bracing element came up after 54", but that does not produce the global collapse of the rack. The global collapse of the structure appears after 1'52", with the buckling of the first level of bracing elements, as show in Figure 6.

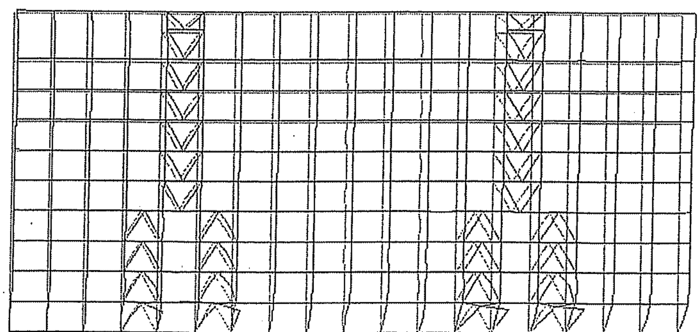

Fig. 6. Initial structure – collapse of down-aisle direction under ISO fire

This poor fire resistance is due to the important values of the imposed displacements produced by the thermal elongation of continuous rails over 60m. These displacements introduce high force levels in the bracing elements. even for small amounts of temperature in the fire compartment. Slotted holes for rail bolted connections were considered then in several locations in order to avoid this phenomenon, combined with several bracing systems. The best ISO resistance times were obtained by cutting off the rail continuity in the middle of the structure, for all levels. Half of the structure may be then considered for the numerical analysis. Having cut the structure in two parts, the bracing system must be strengthened. in order to ensure enough lateral stiffness under wind action at room temperature.

Considering the modified structure. the global collapse is produced by the local buckling of some bracing elements, which leads to the collapse of the adjoining uprights. after 7'46". as shown in Figure 7.

3.1.3. Conclusions of the study under ISO fire

The numerical study shows that it is possible to increase the ISO fire resistance of the structure from less than 2 minutes to around 7 minutes, by modifying some constructional details, with an insignificant increase of steel quantity. However, even if the resistance time of the modified structure represents three times as much as the initial one, it still represents only about half of the required 15 minutes of fire resistance for this type of building. Further improvement on resistance time may be achieved only by strengthening the steel sections of all elements of the modified structure, thus modifying by an important amount the steel quantity.

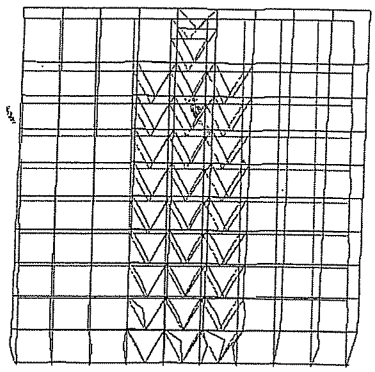

Fig. 7. Modified structure – collapse of down-aisle direction under ISO fire

3.2 Mechanical analysis under natural fire

A more realistic approach for the fire action is to consider a natural fire, taking into account the pre-flashover phase and different physical parameters, concerning the combustible and the building itself.

In order to determine the temperature - time curves for the thermal analysis of cross-section elements of Procter & Gamble storage building, using the combined `Two Zone` and `One Zone` model, the computer program ***OZone***, developed at the University of Liege, was used. Function of the fire spread area and height of hot zone or temperature in the hot zone, a transition from the `Two Zone` model to `One Zone` model, with an uniform temperature in the entire compartment, may occur. The flashover moment is considered when the temperature in the compartment reaches 500°C.

There are no important openings in the P&G storage building. There are no windows, only normal doors for personnel access. Smoke outlets are provided in the ceiling, for 2% of the surface. The fire load density was evaluated to 8400 MJ/m^2, taking into account the combustible provided by the stored goods, on the 25 m height of the building, and the maximum rate of heat release is of 8620 kW/m^2, according to a previous study made by CTICM - France [8].

A very important parameter for the evolution of the temperature-time curve is the fire growth rate. Recent tests on rack fires made in The Nederland, at TNO, demonstrate that the fire growth rate is higher than 'Ultrafast', to which corresponds a constant of time of 75 seconds in a t^2 model. For P&G building, a time constant of 66 seconds was taken into account as the time to obtain 1 MW of heat release, which represents the fastest fire growth rate obtained in the tests.

Considering these parameters, the temperature-time curve for the hot zone obtained with the *OZone* program is shown in Figure 8. The compartment is under a two zone situation until 17 minutes after the fire beginning, when the interface of the two zones reaches less than 20% of the building height, so one of the criteria for one zone transition is fulfilled. The flashover phase is reached after 24 minutes.

After 10 minutes of fire, according to the *Ozone* results, the smoke height is around 20m and the temperature in the lower zone is less than 30^{O}C, so the smoke and the temperature do not endanger the people evacuation.

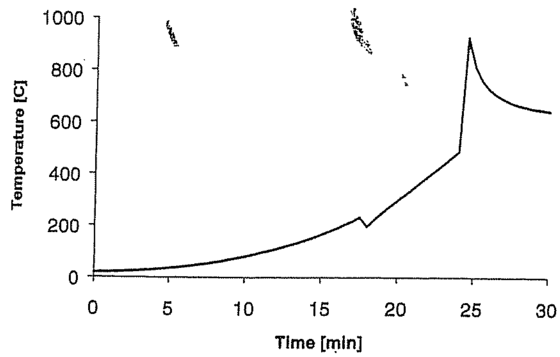

Fig. 8. Natural fire : Temperature - time curve for upper zone

3.2.1. Mechanical analysis of the rack under localised natural fire

For the rack where the fire starts, the fire scenario supposes that a column and the adjoining rails are subjected to localised fire. Standardised ISO fire model was considered for the temperature evolution of the localised fire. The rest of the rack is under the influence of the two zones of temperature distribution, as Figure 9 suggests. Table 1 presents the time resistances for cross-aisle and down-aisle directions, for initial and modified structure. Both down-aisle and cross-aisle directions of the initial structure have a resistance time around 6 minutes, function of the location of the localised fire. The numerical analysis indicates that the collapse of the upright under localised fire leads to the global collapse of the entire rack.

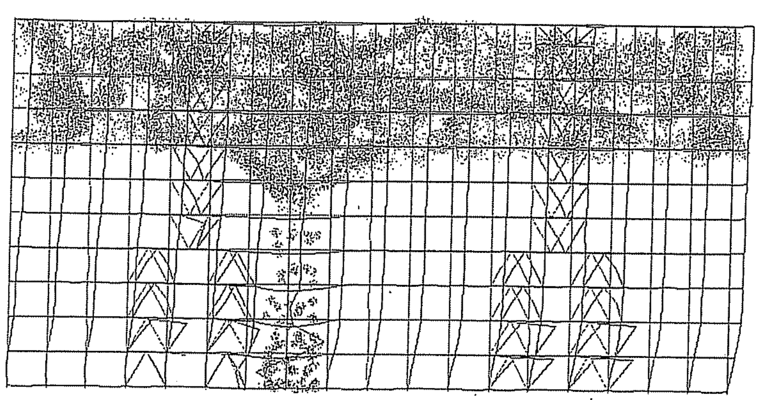

Fig. 9. Initial structure – collapse of down-aisle direction under natural fire

Tab. 1. Collapse of the rack under localised fire

Direction	Initial structure	Modified structure
Cross aisle	6' 05"	7' 41"
Down aisle	5' 55"	7' 30"

The modified structure, considering slotted holes for rail and traverse bolted connections on cross-aisle direction, and the modified down-aisle bracing system, have slightly greater resistance times. The collapse of the upright in fire leads, as for initial structure, to the collapse of the entire rack. The difference is that, for the same fire location, bracings of the modified structure do not present any local buckling before the upright collapse.

3.2.2. Mechanical analysis of current racks under natural fire

The numerical analysis of the rack under localised fire demonstrated that its collapse cannot be avoided after 6 minutes for the initial structure and after 7 minutes for the modified one. For a fire scenario considering that the fire starts on the rack in the middle of the building, after this time it can be considered that the building is cut in two parts, as shown in Figure 10.

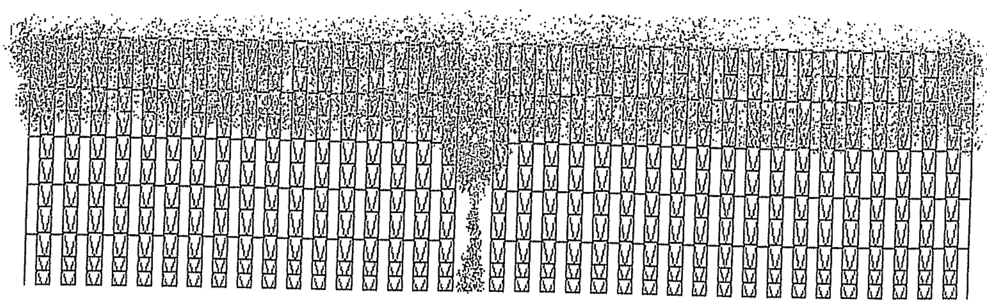

Fig. 10. Cross-aisle configuration after collapse of the first rack

The working hypothesis is that the collapse of a rack produces the breaking of the horizontal elements between cross aisle frames so it does not produce the collapse of adjoining frames. Therefore, in order to ensure that the chain collapse is avoided, it is recommended to design the horizontal elements connections to handle the necessary compression and tension efforts, due to the forces induced by the wind and by the movement of the wagons of automatic transport system, but to have poor resistance for relative displacements between frames in both vertical and horizontal directions.

After the collapse of the first rack, it can be considered that the fire spreads to the two adjoining frames, and they are under the influence of a localised fire. Thus, after another 6 minutes for the initial structure or 7 minutes for the modified one, it may be considered that the collapse of these two racks is also produced. The localised collapse of the racks in the middle of the building may continue in the same manner, without producing progressive collapse, considering the breaking of the horizontal elements.

The global collapse of the entire structure corresponds to the moment of collapse of other current racks under the influence of the two zones of temperature, but not in localised fire. The times corresponding to the global collapse of cross and down-aisle directions, for initial and modified structure under the influence of the two zones of temperature are shown in Table 2.

Tab. 2. Current rack collapse

Direction	Initial structure	Modified structure
Cross aisle	*20' 35"*	*24' 30"*
Down aisle	20' 40"	24' 40"

It may be observed that the modified structure survives long enough to reach the time corresponding to the flashover phase. After this limit, it would be difficult to obtain more structural resistance, taking into account the high level of temperatures in the compartment.

3.2.3. Conclusions of the study considering natural fire

The collapse of the first rack under localised fire, after 6 minutes for the initial structure or 7 minutes for the modified one, does not present a danger, because normally at this moment the persons which evacuate the building cannot be in the area of engulfed fire.

Considering the rescue service safety, which may arrive in less than 15 minutes after the fire beginning, the main risk for firemen who enter the building is the progressive collapse of the racks. The present study tends to indicate that no progressive collapse has to be feared as long as the flash over does not occur. When and if this happens, the structure is certainly in great danger of immediate collapse but, at this time, this is not anymore a real issue for the firemen, who should normally have evacuated the compartment.

4. CONCLUSIONS

The mechanical analysis under elevated temperatures, considering the standardised ISO fire in the entire fire compartment, showed that the 15 minutes of fire resistance criteria imposed for this type of industrial building is difficult to obtain. First, this is due to the low thermal massivity of the cold-formed profiles normally used to build rack systems. A second reason is that the partial load factors for fire accidental situation in case of storage systems are much higher than for other types of buildings. Last but not least are the important indirect effects due to dilation of such building systems, often continuous over 100m, and supposed to be uniformly heated.

Anyway, by modifying some constructional details, the ISO fire resistance time for the initial studied structure may be somewhat improved, from 2 to 6 minutes, without altering by an important amount the steel quantity. Further increase of the resistance time cannot be achieved without reinforcing the steel sections of all elements of the modified structure, thus increasing significantly the steel quantity.

A more realistic approach is to take into account a natural fire scenario. The mechanical analysis under natural fire shows that the rack where the fire starts collapses rather quickly. The numerical analysis shows that the global collapse of this rack cannot be avoided. This does not present a significant danger for trained people authorised to access the building, because normally at this moment they are not supposed to be in the area of the engulfed fire. On the hypothesis that the horizontal traverse element break at the time of the collapse of a rack, the collapse of this rack does not activate a chain collapse of the entire building, which is to be avoided in order not to endanger the firemen who would try to water the fire from a place out of the engulfed fire. The other racks are heated under the effect of the hot gas accumulation under the ceiling, and the time corresponding to the ruin of these racks is representing the global collapse of the entire building. Both the initial and the modified structure present a fire resistance time before global collapse greater than 15 minutes, moment assumed to correspond to the firemen arrival. Considering the proposed constructional detail modifications, the structure presents a better resistance time, being able to stand until the moment of the flashover phase, an event that leads anyway to the firemen evacuating the compartment.

After the flashover moment, it is difficult to maintain the structural stability, taking into account the high level of temperature in the compartment. The flashover may be avoided by the intervention of the fire brigade, which is supposed to limit the fire development. The fire scenario considered in the natural fire study does not consider the sprinkler system or the firemen action after their arrival.

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