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Computer Model for the Fire Resistance of Composite Structures

Programme de calcul pour l'analyse de la sécurité au feu de structures mixtes

Rechenprogramm für die Feuerwiderstandsbemessung von Verbund-Konstruktionen

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SUMMARY

The behaviour of buildings during fire is a complex problem. For single elements such as one column or one beam, simplified methods or full scale fire tests in furnaces allow to determine the fire resistance. For complete structures, a numerical method as used by the program "CEFICOSS" enables to predict the fire behaviour. In this contribution the possibilities of this program and simulations of composite steel-concrete frames are described.

RÉSUMÉ

Le comportement des bâtiments lors d'un incendie est un problème complexe. Pour des éléments seuls, tels qu'une colonne ou une poutre, des méthodes simplifiées ou des essais au feu en vrai grandeur dans des fours permettent de déterminer la résistance au feu. Pour des structures complètes, une méthode de calcul numérique telle que celle du programme «CEFICOSS» permet de prédire le comportement au feu. Dans cet article sont décrites les possibilités de ce programme ainsi que des simulations de cadres mixtes acier-béton.

ZUSAMMENFASSUNG

Das Verhalten von Gebäuden im Brandfall stellt ein komplexes Problem dar. Für einzelne Tragelemente wie z.B. eine Stütze oder ein Träger, können vereinfachte Rechenmethoden oder Brandversuche im Massstab 1:1 zur Bestimmung des Feuerwiderstandes benutzt werden. Zur Berechnung des Feuerverhaltens einer vollständigen Struktur kann nur ein numerisches Rechenmodell wie das jenige des Programms „CEFICOSS" dienen. In diesem Artikel werden die Möglichkeiten dieses Programms sowie die Simulation von Verbundrahmen beschrieben.

1. INTRODUCTION

The probability of coming across fire in residential buildings, hotels, schools, hospitals or industrial plants depends on many factors, amongst which the age of the buildings and the level of confidence of the safety precautions are capital.
However that probability can never be reduced to zero, because it is impossible to completely avoid the presence of all burning materials as well as it is impossible to imagine a world free of any defects and of any spiteful act. That's why it is necessary to give a sufficient fire resistance to buildings.
There are various approaches to study the fire resistance of structures. The first approach, which still remains the most common approach up to now, is the use of full scale tests in furnace in which ISO-fire conditions are simulated. Another approach is given by the simplified calculation methods. But these methods, including the fire tests, can only be used for single elements like one beam or one column [1].
Thus it results that a satisfactory knowledge of the behaviour of a structure as a whole during fire and of its way to collapse can only be obtained by an accurate numerical computation method. Such a method is included in the computer program "CEFICOSS" [2,3].

2. NUMERICAL COMPUTER MODEL

CEFICOSS stands for Computer Engineering of the FIre resistance of COmposite and Steel Structures. This numerical program performs a step-by-step simulation of the behaviour of columns, beams or plane frames submitted to the fire [4,5,6].
The first part of the program calculates the temperature distribution in the cross-sections of the structure. In order to make the step-by-step simulation of the static behaviour, the temperature distribution is calculated at different instants (f.i. every minute) defined by the user. The problem is considered to be two dimensional. The cross sections are discretized by a rectangular mesh. By indicating which material (steel, concrete or insulating material) is present in each mesh, it is possible to analyse various shapes of pure steel, reinforced concrete or composite steel-concrete sections. The transient conductive equations are solved by an explicite finite difference scheme, the time step of which being automatically calculated in order to ensure convergence with the shortest computing time. As thermal conductivity and specific heat of the building materials are temperature dependent, this time step varies during the calculation.
The boundary conditions are convection and radiation or symmetry. The outside world is represented by the temperature of the gases with various possibilities; ambient temperature, ISO curve or any other curve including a cooling down phase. Evaporation and transportation of the moisture in wet materials is considered. Though it is possible to perform the thermal and the static calculations simultaneously, it is more convenient to store the temperatures on a file that can be read for different static calculations with the same cross-section.
Instead of an ultimate state design (which load can be sustained by a structure after 60 minutes of ISO fire?), CEFICOSS performs the realistic continuous simulation of a structure in a fire (how long will a structure be able to sustain the applied load). That means that the load is first applied in successive steps on the structure at ambient temperature. If collapse has not occured, stresses, strains and displacements are stored on a file. From this moment, keeping the loads generally unchanged, the temperatures are increased in the sections and the new values of

stresses, strains and displacements are computed. This is done up to the time when equilibrium can no more be obtained, which indicates that collapse has occured.
A finite beam element is used with two nodes and six degrees of freedom. The equations are written in an updated lagrangian formulation. The two hypothesis of Bernoulli and Von Karmann are made as well as the one of small incremental displacements ($\sin \Delta \theta \simeq \Delta \theta$). In order to prevent axial locking, the mean value of the non-linear term of the axial strain is considered. Large displacements are taken into account.
Stress-strain relationships in building materials are non-linear and temperature dependent. Different possibilities are offered as the quadro-linear or elastic-elliptic relationships for steel, and the descending branches for concrete. Thermal elongations as well as residual strains are explicitely considered, while creep is implicitely introduced in the stress strain relationships.
In order to have the shortest possible computing time with a simultaneous sufficient accuracy when the failure time is approached, the time step of the static calculation is controlled by the minimum proper value of the stiffness matrix.

3. SIMULATIONS PERFORMED BY CEFICOSS

Numerous practical fire resistance calculations have been performed which allow to consider this numerical computer model as a quite general and most credible engineering tool. Moreover very recently N-M interaction failure diagrams buckling included, have been established for composite construction elements and for unprotected heavy steel columns [7,8]. Besides the effect of local fire on a two level frame has been analysed for the first time [9]. In this contribution it will be shown that it is quite possible to analyse the effect of a local fire on a six level composite frame.

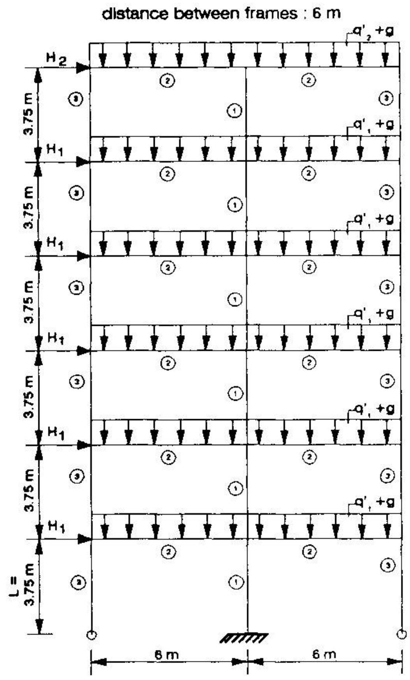

Fig. 1 Static System of the sway frame

3.1.Frame definition

The chosen composite frame has 6 levels and 2 spans. The geometrical configuration is shown on figures 1,2 and 3.
- The mechanical properties of the materials are defined by the standardized qualities: St 37 for steel profiles, BST 500/550 for rebars and B 40 for concrete.
- Three static systems are considered: braced frames with rigid or hinged beam-column connections and a sway frame. For the braced frame with hinged connections, the columns are continuous. For the sway frame the ground end condition is fixed for the central column and hinged for the other ones. For the braced

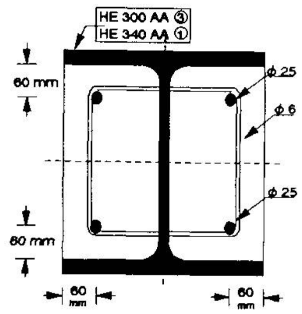

Fig. 2 Column cross section (number 1 and 3)

frames the three columns have hinged ground end conditions and the horizontal stability is supposed fulfilled by a central core (see figure 10).

- For each static system the structure has been designed and optimized for service conditions with just the minimum required safety.
- The loads are divided into proper weight g, service load q', and horizontal wind load H. The basic load combination called B.L. is equal to 1,35*g + 1,5*q' + 1,12*H.
- For each static system three ISO-fire scenarios have been studied which affect either
1)the lower left column and beam or
2)the same but also the lower central column or
3)the whole lower frame.
- For each fire scenario two loadings are considered: B.L/3.5 or B.L/2.3.
- The 18 frames described hereabove have been calculated by "CEFICOSS" so that their global behaviour under fire and therefore their fire resistance time is known.

3.2. Comparison between global system simulation and calculation of single element

For each case the critical element in the structure under hot condition was considered. This element was analysed by CEFICOSS under fire conditions as a single element submitted to the internal forces existing before fire. The column buckling length was adapted to take into account the proper end conditions. The fire resistance times found by this simplified method and by the global system calculation are noted in the figure 10. It shows that both methods give similar results for braced frames. But this is not true for sway frames. That's why we are going now to have a look at the simulation of a sway frame with f.i. the fire scenario 2 and the loading B.L./2.3 (figures 1 and 10). In this case the cross sections of the construction elements can be seen in figures 2 and 3.

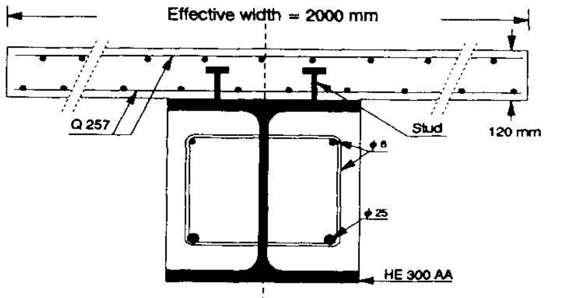

Fig. 3 Beam cross section (number②)

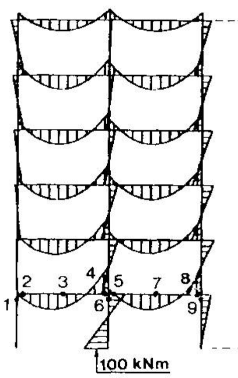

Fig. 4

Bending moments before heating

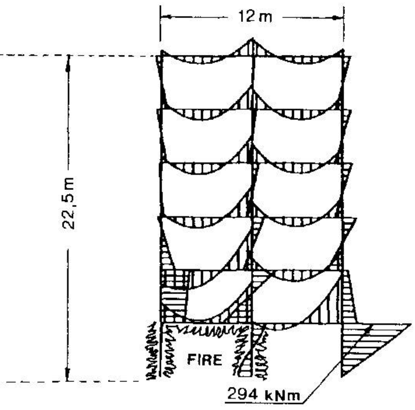

Fig. 5

Bending moments just before failure at 123'

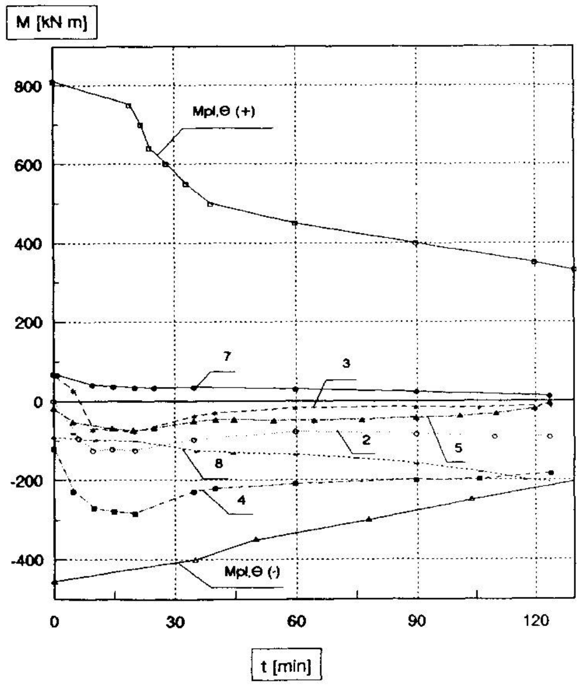

Fig. 6 Variation of bending moments in the beams during fire

3.3. Sway frame

The diagram of bending moments before heating and just before the failure are shown on figures 4 and 5. It can be seen that the bending moment distribution changes strongly during the fire.

- For the beams the variation of the bending moments can be drawn in a diagram where the ultimate positive bending moment Mpl,θ (+) and the negative one Mpl,θ(-) are represented in function of the time. This diagram shows that no plastic hinge occurs in the beams (figure 6).

- For the columns the situation is more complex because the axial force, the bending moment distribution along the column, the buckling length and the second order effect play a part. Moreover all these parameters change differently in function of the fire evolution.

- But the horizontal displacement curves in function of the time of the top of the lower columns enable to conclude that the failure is produced by the buckling of the whole lower frame. (figure 7). In fact the buckling of the central column occurs first but is followed a few seconds later by the simultaneous buckling of the left and right columns. This phenomenon also appears in the figure 8 showing the vertical displacements of the top of the lower columns.

3.4. Conclusions

- The opposite figure 9 shows the deformed structure just before the failure. It can be seen that the whole structure is submitted to important displacements. So it is not possible to calculate only a single element in order to obtain the fire resistance time of the whole frame as it is the case for braced frames. This is noted in figure 10 where the results of numerous global system simulations are recorded as well for the braced frames I and II as for the here more detailed sway frame III.

- This numerical procedure is fully in line with Part 10 "Structural Fire Design" of Eurocodes 2, 3 and 4 [10].

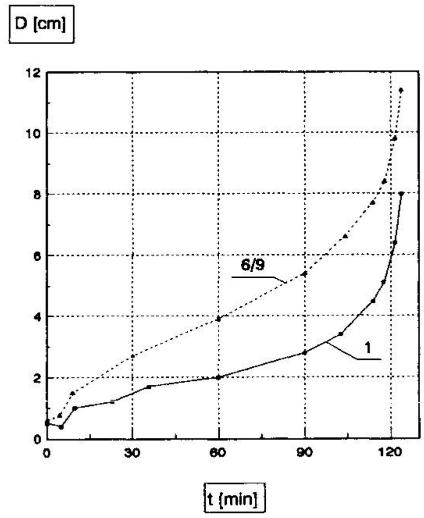

Fig. 7 Horizontal displacements of the top of the lower columns

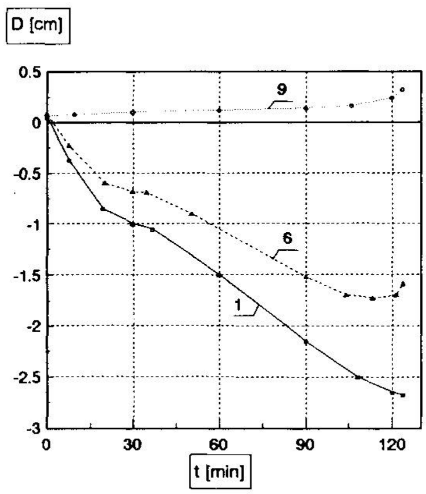

Fig. 8 Vertical diplacements of the top of the lower columns

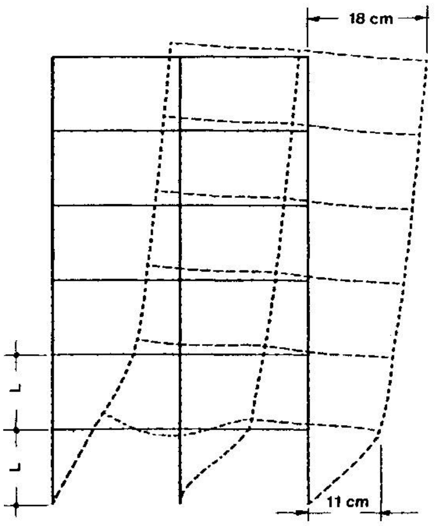

Fig. 9 Total displacement of the structure just before failure at 123'

Basic Load (B.L.) : 1.35*g + 1.5*q' + 1.12*H

CALCULATED BY CEFICOSS

Global system calculation					Single column analysis					
System	Fire Scenario	Loading	t (min)	Failure type : Buckling of	Loading N	Loading M1	Choosen column element	t (min)	dt (%)	System
I	1	B.L/3.5	75'	Lower left column	303	8.8	Lower left column	77'	2.6	N, M_1, 0.7*L, $M_2 = 0$
		B.L/2.3	53'	Lower left column	461	13.4	Lower left column	49'	-8.2	
	2	B.L/3.5	82'	Lower left column	303	8.8	Lower left column	77'	-6.5	
		B.L/2.3	57'	Lower left column	461	13.4	Lower left column	49'	-16.3	
	3	B.L/3.5	77'	Lower left column	303	8.8	Lower left column	77'	±0.0	
		B.L/2.3	48'	Lower left column	461	13.4	Lower left column	49'	2.2	
II	1	B.L/3.5	88'	Lower left column	319	1.7	Lower left column	94'	6.4	
		B.L/2.3	65'	Lower left column	485	2.6	Lower left column	68'	4.4	
	2	B.L/3.5	88'	Lower left column	319	1.7	Lower left column	94'	6.4	
		B.L/2.3	65'	Lower left column	485	2.6	Lower left column	68'	4.4	
	3	B.L/3.5	79'	Lower left column	628	2.7	Lower left column	94'	16	
		B.L/2.3	50'	Lower central column	956	4.1	Lower central column	49'	-2.0	
III	1	B.L/3.5	197'	Global failure of the whole frame	No equivalent single element analysis available					
		B.L/2.3	168'							
	2	B.L/3.5	206'							
		B.L/2.3	123'							
	3	B.L/3.5	110'							
		B.L/2.3	68'							

Fig. 10 Comparison between global system calculation and the simplified approach given by a single column analysis

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