A Comparison Between Five Structural Fire Codes Applied to Steel Elements

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ABSTRACT

A comparison program has been established concerning the simulation of the static behaviour of steel columns submitted to fire [1]. The stress strain relationships in steel are those recommended in EC3, part 10 [2]. The five numerical codes used in this comparison are briefly described, namely CEFICOSS, DIANA, LENAS, SAFIR and SISMEF. A description of 8 tests is given: Lee's frame at ambient and at elevated temperatures, an eccentrically loaded column at ambient temperature, at uniform elevated temperature and under ISO heating and finally an axially loaded column in the same three cases (ambient, uniform and ISO).
The evolution of the horizontal displacement is graphically given for each test, as well as a table summarising the results in term of ultimate resistance.
The five programs compare reasonably well when the final resistances are considered, which would be the case in a situation of design for a real structure. In all the tests, the maximum difference between two different programs is 6%.
Differences may occur in the evolution of displacements, mainly due to the way that the residual stresses are considered, or to the fact that the non uniform temperature distribution has sometimes been replaced by a uniform temperature equal to the average value of the non uniform distribution.
Keywords : Fire resistance, Steel, Simulation, Comparison, Residual stress, Column.

INTRODUCTION

Since the first of July 1992, a research program [1] is running with the financial support of the ECSC with the aim of determining the buckling curves of hot rolled H steel sections submitted to fire, in the hypotheses of Eurocode 3, part 10 [2]. The stress strain relationships and thermal properties of steel presented in [2] are still present in the last version of EC3 part 1.2. issued in July 1993 [3]. The four organisations of the authors are responsible for the theoretical and numerical aspects, whereas LABEIN and ENSIDESA in Spain are in charge of the experimental program. As different fire codes from different organisations would be used as numerical tools in this research project, it was decided to check the consistency of the results when those different programs are applied on the same structural elements.
The main results of this comparison are presented here in order to show what level of consistency or what differences appeared, and to provide a series of points of comparison to be used by other developers of codes. Readers wishing to receive the results files can contact the first author at fax number int. + 32.41.66.95.34. Those points of comparison could also be a first help to verify the validity of the general calculation models, as required under 4.3.4., P(1) of EC3, part 10 [2].

THE CODES

The five codes are;

CEFICOSS[4,5,...,10], ProfilARBED-Recherches, Luxembourg. CEFICOSS stands for Computer Engineering of the FIre resistance of COmposite and Steel Structures.

DIANA, T.N.O. Delft. DIANA, an acronym for DIsplacement ANAlyser, is a general purpose package for structural analyses, transient potential (heat) flow problems and fluid dynamics.

LENAS-MT [11], C.T.I.C.M. Saint Rémy lès Chevreuse and TAKENAKA Tokyo. Large deflection Elasto plastic Numerical Analysis of Structures - Member in Transient state.

SAFIR, University of Liege, Belgium. This software is, after CEFICOSS, the second generation of structural fire codes developed in Liège.

SISMEF, C.T.I.C.M. Saint Rémy lès Chevreuse. Simulation a l' Incendie des Structures Mixtes par Elements Finis. Composite frame analysis considering partial connections between concrete slab and steel beam.

Some features are common for the five programs : evolution of the structure under constant load simulated as the temperatures increase, large displacements, non linear and temperature dependent material properties (structural and thermal if relevant). The main differences are identified in table 1.

TABLE 1. Main differences between the codes.

	CEFICOSS	DIANA	LENAS-MT	SAFIR	SISMEF
Thermal analysis	2D	3D	*1	3D	*1
Formulation	finite difference	finite element	-	finite element	-
Structural analysis	2D	3D	3D	3D	2D
Beam formulation	Bernoulli	Mindlin	Bernoulli	Bernoulli	Bernoulli
Nodes	2	3	2	3	2
DOF per node	3-3	6-6-6	7-7	7-1-7	3-3
Sectional discretization	rectangular fibres	Gauss-Simpson	rectangular fibres	triang. or quadr. fibres	rectangular fibres
Longitudinal integration	Gauss	Gauss	linear between the nodes	Gauss	Gauss
Large displacements	updated lagrangian	total lagrangian	updated lagrangian	total corrotational	updated lagrangian
Resid. stresses	initial strains	initial stresses	initial strains	initial strains	initial strains
Material law	uni axial	multi axial *2	multi axial *2	uni axial	uni axial

*1 Thermal results are taken from TASEF, written by Wickström [12]

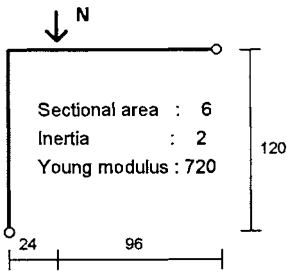
*2 Von Mises yield-criterion and isotropic strain hardening

THE TESTS.

No imposition was made concerning the discretization. Each author was responsible to chose a sufficiently fine discretization as to ensure convergence of the result with respect to the discretization, according to his experience with his own program.

STRUCTURE A : LEE'S FRAME [13].

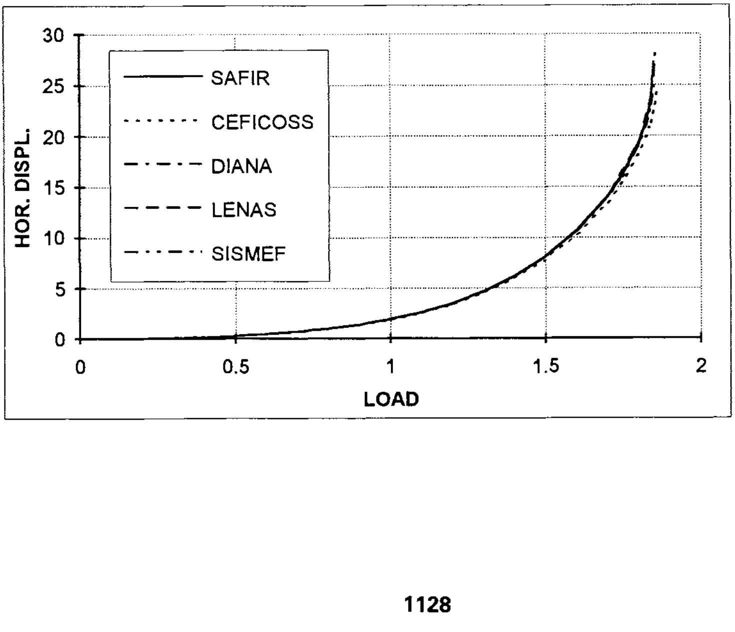
FIGURE 1. Lee's frame (consistant units).



A-1 : LEE'S FRAME AT AMBIENT TEMPERATURE.

Lee's frame is often used as a reference structure to check the geometrical non linearity of programs at ambient temperature. The material is elastic, but the displacements are very large. It was analysed at ambient temperature. Fig. 2 presents the evolution of the horizontal displacement of the point where the load is applied, as a function of this vertical load.

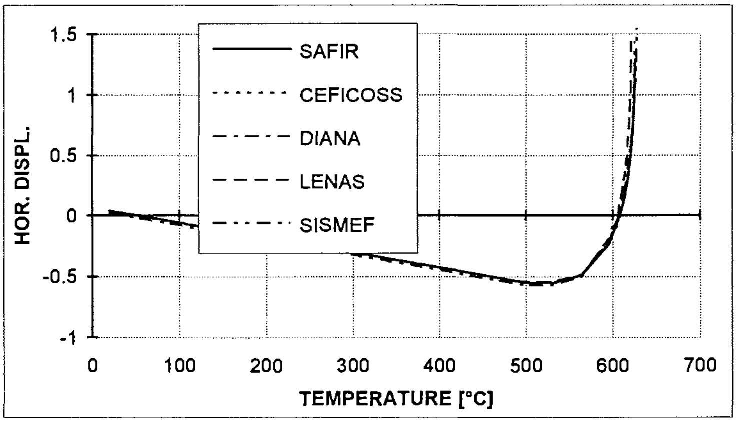
FIGURE 2. Lee's frame at ambiant temperature.



A-2 : LEE'S FRAME UNDER UNIFORMLY INCREASING TEMPERATURE.

The same structure is supposed to be made of EC3 steel with $E_s = 720$ and $f_y = 3$ (consistent units). A load of 0.2 is applied and maintained as the frame is uniformly heated. This test allows to check whether the thermal strains are correctly considered, whether redistribution of the solicitations is correct and what the effects of plasticity are at elevated temperatures. Fig. 3 presents the evolution of the horizontal displacement of the point where the load is applied, as a function of the temperature in the section.

FIGURE 3. Lee's frame under uniformly increasing temperature.



STRUCTURE B : ECCENTRICALLY LOADED COLUMN.

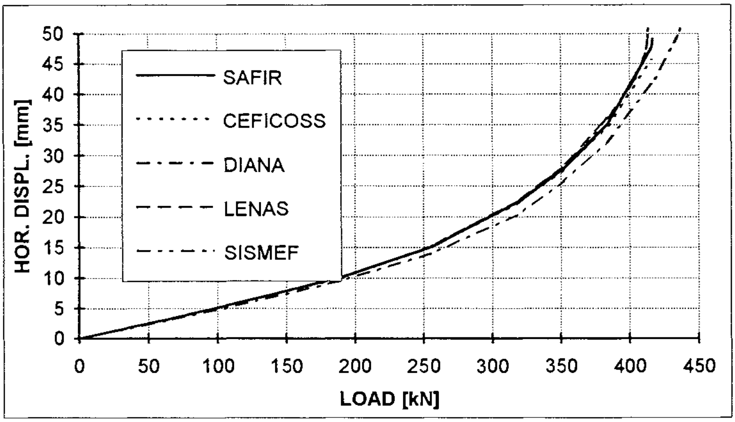
Description :
- simply supported column, H = 4 m, buckling around the minor axis,
- sinusoidal imperfection of 4 mm, dead weight neglected.
- HE 200 B, EC3 steel, f_y = 235 MPa, bitriangular residual stress distribution with a maximum value of 117.5 MPa.
- Loading : at both ends, axial load N + bending moment M = N x 100 mm (effects adding to the imperfection).

This column was analysed because a further step of the aforementioned research project [1] is to analyse the interaction formula R(5) from 4.2.2. in EC3 [2], proposed for members with combined axial force and moment.

B-1 : ECCENTRICALLY LOADED AT AMBIENT TEMPERATURE.

The column is analysed under increasing load and Fig. 4 provides the evolution of the horizontal displacement at mid height as a function of the vertical load.

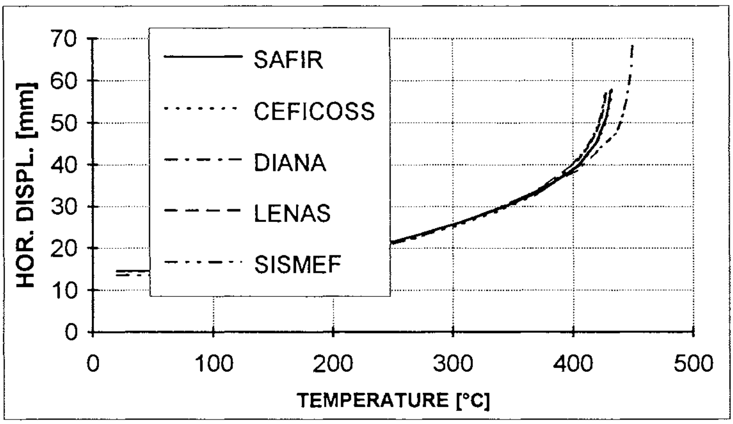
FIGURE 4. Eccentrically loaded column at ambiant temperature.



B-2 : ECCENTRICALLY LOADED AT UNIFORMLY INCREASING TEMPERATURE.

This case of uniform temperature is representative of a thermally insulated column, where the insulation gives time to the high thermal diffusivity of steel to homogenise the thermal distribution in the section. A load of 250 kN (+ M = 25 kN m) is applied and maintained as the column is uniformly heated. Fig. 5 gives the evolution of the horizontal displacement at mid height as a function of the uniform temperature in the section.

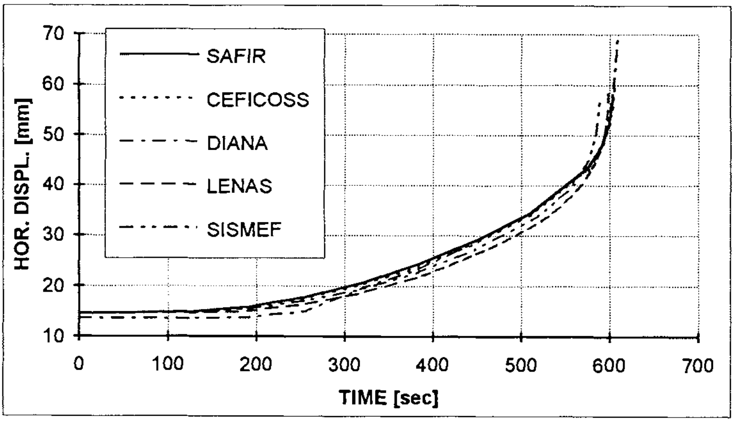
FIGURE 5. Eccentrically loaded column under increasing uniform temperature.



B-3 : ECCENTRICALLY LOADED UNDER ISO HEATING.

With the same load applied, the column is submitted to the ISO curve. The temperature distribution is calculated according to Eurocode[14]. The thermal gradients arising in the section can be considered as an additional structural imperfection. The evolution of the horizontal displacement as a function of time is presented on Fig. 6.

FIGURE 6. Eccentrically loaded column under ISO heating.



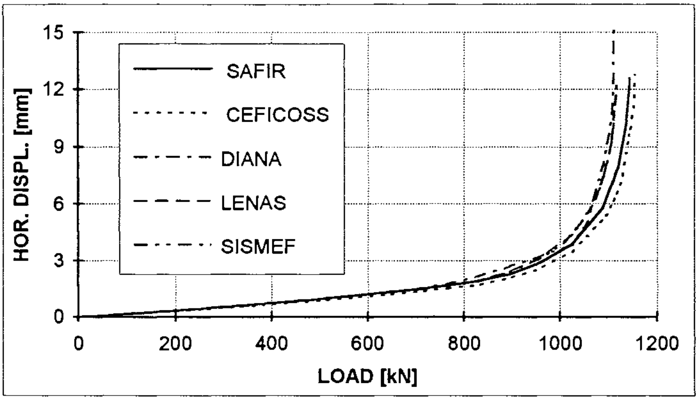
STRUCTURE C : AXIALLY LOADED COLUMN.

The column and the section are the same as for structure B.
Loading : axial load N.

C-1 : AXIALLY LOADED AT AMBIENT TEMPERATURE.

The column is analysed under increasing load and Fig. 7 provides the evolution of the horizontal displacement at mid height as a function of the axial load.

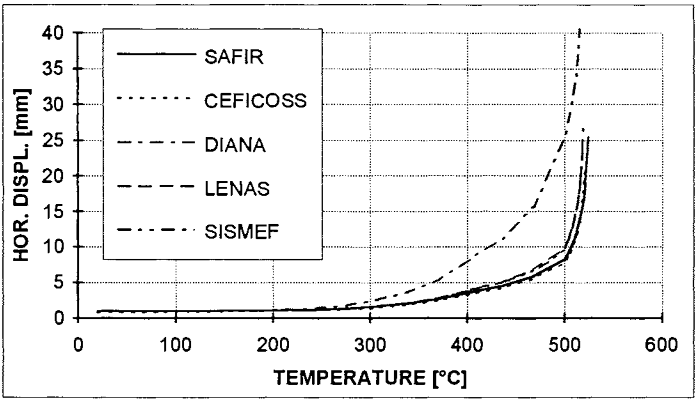
FIGURE 7. Centrically loaded column at ambiant temperature.



C-2 : AXIALLY LOADED AT UNIFORMLY INCREASING TEMPERATURE.

An axial load of 500 kN is applied and maintained as the column is uniformly heated. Fig. 8 gives the evolution of the horizontal displacement at mid height as a function of the uniform temperature in the section.

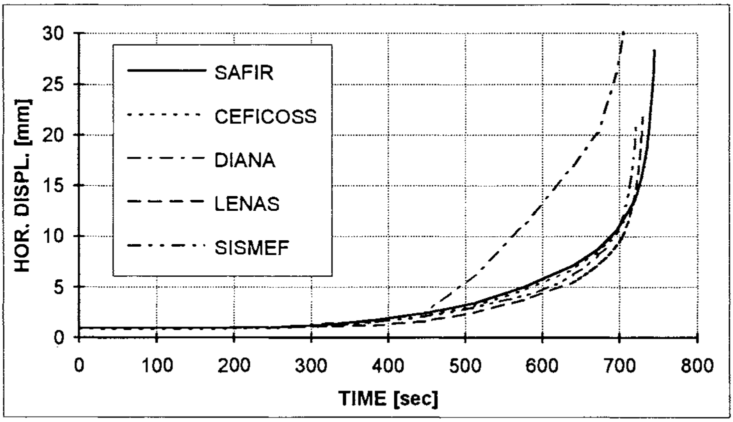
FIGURE 8. Centrically loaded column under increasing uniform temperature.



C-3 : AXIALLY LOADED UNDER ISO HEATING.

With the same load applied, the column is submitted to the ISO curve. The evolution of the horizontal displacement as a function of time is presented on Fig. 9.

FIGURE 9. Eccentrically loaded column under ISO heating.



COMMENTS ON THE RESULTS

General comment :

Some of the curves presented in Fig. 2 to Fig. 9 appear as made of linear segments, not because the programs really predicted such a discontinuous behaviour (sudden plastification of the section, for example), but because only discrete points have been calculated in the diagrams and linear interpolation applied on the results when plotting the drawings.

A summary of the results is presented in table 2.

TABLE 2 : Summary of the results.

	A-1	A-2	B-1	B-2	B-3	C-1	C-2	C-3
	Load	Temp.	Load	Temp.	Time	Load	Temp.	Time
SAFIR	1,85	626°C	417 kN	432°C	604 sec	1144 kN	524°C	745 sec
CEFICOSS	1,86	625°C	416 kN	433°C	606 sec	1154 kN	524°C	745 sec
DIANA	1,855	628°C	437 kN	450°C	609 sec	1113 kN	515°C	717 sec
LENAS	1,84	621°C	414 kN	428°C	599 sec	1116 kN	518°C	730 sec
SISMEF	1,84	625°C	414 kN	427°C	589 sec	1117 kN	519°C	722 sec
Analytical	1.855					1170 kN		

For test C-1 the analytical value is provided by EC3, part 1. For a slenderness of78.90,European buckling curve c gives : Nult = 0.657 x Npl = 0.657 x 1835 kN = 1170 kN.

LEE'S FRAME.

The results of test A-1 compare very well with the analytical solution from [13], where the ultimate load is given as 1.855. All program find a result that differs by less than 1% from this analytical value. This comes as no surprise considering that Lee's frame is a commonly analysed structure for the validation of non linear codes at ambient temperature. The success with this test is therefore a minimum requirement for non linear fire codes.
When analysed at elevated temperature (test A-2), Lee's frame has also the same response according to the five programs which differ by no more than 1% considering the ultimate temperature. This gives some confidence that the law of thermal elongation and the stress-strain relationship have been similarly (and hopefully correctly) introduced in the five codes.

ECCENTRICALLY LOADED COLUMN.

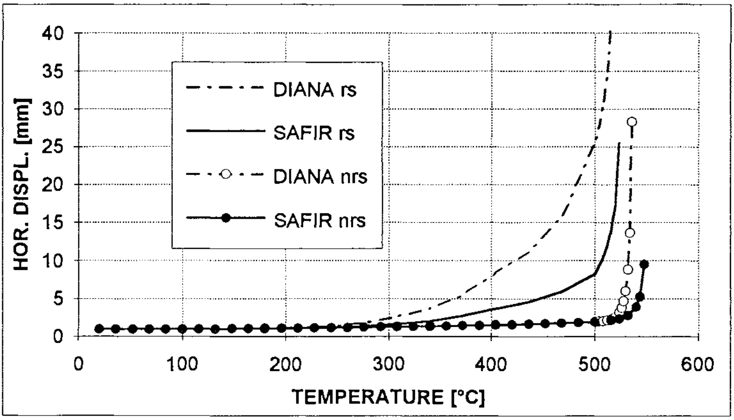
The eccentrically loaded column introduces the effect of residual stresses. The four program specifically dedicated to fire analysis differ by less than 3 %. The differences between DIANA and the average value of the results given by the other four codes is 5%, 5% and 2% for the tests B-1, B-2 and B-3 respectively.

AXIALLY LOADED COLUMN.

The structure C has the same structural imperfections as the structure B (residual stresses and non uniform temperature distribution). The maximum difference between the five programs is, in term of ultimate value, less than 4%. The displacement history calculated by DIANA is significantly different from the results provided by the other programs for tests C-2 and C-3, with large displacements appearing earlier and being more important at the end of the simulations, while the results by DIANA are close to the others at the beginning of the simulations.
The reason of this difference has not been clearly identified. Some possible reasons might be;
1. The non uniform temperature distribution in case of ISO heating.
SAFIR and CEFICOSS have their own thermal routines directly linked to the static routines.
LENAS and SISMEF simulations are based on thermal results from TASEF[15].
DIANA has its own thermal routines, but not linked as a standard option to the static routines. The transfer of the thermal results to the static calculation has not been made here in order to reduce the amount of work to be done and the tests B-3 and C-3 have been calculated with uniform temperature distribution. This is yet not thought to be a major cause of the difference because, firstly the uniform temperature calculated by DIANA was similar to the average value of the non uniform temperature calculated by the other programs, secondly there is much less difference in test B-3, *although the test B-3 has also been simulated by DIANA with a uniform temperature distribution instead of a really non uniform distribution.*
2. The way how the residual stresses are considered could be the main factor.
SAFIR, CEFICOSS, LENAS and SISMEF consider initial values of residual strains, which are then naturally kept constant during the simulation [15, 16].
DIANA considers initial values of residual stresses, which are kept constant during the simulation, except if they are larger than the maximum stress allowed at each temperature.
The influence of the residual stresses and the influence of the way in which they are accounted for is illustrated in Fig. 10 for the case C-2. In this figure, the horizontal displacement calculated by DIANA and SAFIR is plotted, with and without taking into account the residual stresses. It can be seen that both codes provide very similar results when

the residual stresses are not accounted for. The effect of the residual stresses on the failure temperature is not as significant as it is on the deformation behaviour. The way in which the residual stresses are taken into account does not lead to important differences for the eccentrically loaded column (see Fig. 5). Apparently the effect of the eccentricity overrules the effect of the different assumptions with regard to the residual stresses.

FIGURE 10. Influence of the residual stresses and of the way in which they are modelled..



CONCLUSIONS

When applied to a structure where bending is predominant, this comparison confirmed what has already been reported elsewhere [17 p. 8.4.], that most of the simulation programs provide very similar results.

When applied to structures with important axial loads, the different five programs show differences in term of ultimate resistance that would probably be acceptable in a situation of practical design (maximum difference between two programs for all the tests : 6%). LENAS and SISMEF generally lead to very slightly lower ultimate values than SAFIR and CEFICOSS, and DIANA's results are situated either on the safe or on the unsafe side of the results of the four others.

Some differences could be observed in the evolution of displacements, probably due to the different ways that the residual stresses are considered when temperatures increase. The effects of those residual stresses appear to be the most significant in the case of centrically loaded column. This structure is indeed very sensitive to structural imperfections because any additional lateral displacement, even if small, rapidly leads the column toward instability. The effects of the residual stresses tend to decrease when the load is applied with an eccentricity.

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