COMPARISON BETWEEN VARIOUS METHODS FOR THE EVALUATION OF THE FIRE RESISTANCE OF CONCRETE FILLED HOLLOW STEEL COLUMNS

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Hollow steel columns filled with bar-reinforced concrete are used extensively in the construction of high-rise buildings. Many research works devoted to the fire resistance of these profiles have been performed in Europe and in North America. Though calculation methods are now proposed in codes, more practical tools are needed by the design engineers. It is not easy to develop such methods due to the large scatter of experimental results. In this article three methods based on quite different procedures are examined. Comparisons have been made between the results obtained by the three methods and test results. The potentialities of each method are examined, but also the domains in which they should be used with care, or even they should not be used.

Key words: Columns, Composite steel-concrete construction, Fire resistance, Hollow steel sections.

1. INTRODUCTION

The use of concrete filled steel hollow section (CFSHS) columns for the construction of various types of buildings and more particularly for high-rise buildings has become increasingly popular in recent years. They are appreciated by engineers and architects because they have many advantages.

Several research works related to the behaviour under fire conditions of this type of profile have been performed in Europe in the 70's and the 80's [1, 2, 3. 4]. In North America, the studies started in the 90's, and have been mainly conducted in Canada [5, 6, 7]. The calculation and design of this type of elements are now included in codes and standards, like for example in Eurocodes for cold [8] as well as for fire conditions [9, 10].

Though calculation methods are proposed in Eurocode 4, the use of some of them may be very tedious for the design engineers, and it may be interesting to have more practical tools at their disposal. On the other hand, in all the studies mentioned hereabove, it is clearly shown that the experimental results display a large scatter, and it is therefore difficult to propose theoretical formula's or methods which are at the same time safe and economical.

In this article three methods based on quite different procedures will be examined: Kodur's formula's, established on the basis of test results [5, 6, 7] and parametric studies realized by computer programs developed to this aim [11, 12]; POTFIRE computer program, a design tool developed by CTICM [13]; SAFIR, a computer code developed at the University of Liège for the simulation of the structural behaviour under fire conditions [14]. SAFIR has been validated by comparison with many experimental results, particularly for complex composite elements [15, 16].

2. DESCRIPTION OF THE MODELS USED FOR THE COMPARISON

2.1. The method developed by KODUR

In the 90's the National Fire Laboratory and the National Research Council of Canada developed guidelines for the simplified design and construction of concrete-filled HSS (hollow steel section) columns.

Both experimental and theoretical studies, using computer models, were carried out to investigate the influence of concrete filling on the fire resistance and load capacity of HSS columns.

Fifty-eight concrete-filled HSS columns were tested to failure by exposing the columns to fire [5, 6, 7]. Most of the HSS columns tested were subjected to a concentric load. Only three columns were tested for eccentrical loads. Most of the columns were tested with fixed end conditions. Only four of them had different support conditions. These characteristics are important for the development of the formula's and for the analysis of the results given by this method.

Computer models were also developed for predicting the behavior of concrete-filled HSS columns in fire, one for circular sections and one for square sections [11, 12]. They have been used to carry out detailed parametric studies to generate a large amount of data.

Based on the relationships between the fire resistance and the above parameters, formula's for the fire resistance of a concrete-filled HSS column subjected to axial loading were established empirically: one is valid for circular and the other for square columns. These equations have been rearranged in terms of a maximum load for a desired fire resistance rating, which is most useful for designers.

The formula's are not reproduced here; they can be found in [11, 12]. It must be pointed out that limitations exist on several parameters. Some of them will be discussed in the analysis of the results obtained in section 3.

2.2. POTFIRE computer program

POTFIRE computer program is a design tool developed by CTICM in France from a model originally developed in 1992 by COMETUBE. It has been further enhanced in a collaboration with TNO in the Netherlands.

POTFIRE allows either the evaluation of the fire resistance duration of an unprotected concrete filled HSS column under a known design load, or the evaluation of the ultimate load bearing resistance after a given exposure time to the standard ISO fire. It is also possible to take bending moments into account. It deals with circular, square and rectangular sections.

Three versions of POTFIRE, namely V1.2, V2.0 and V3.0, have been used in this study. The first two are based on the same calculation principles. They only differ in the models used for the thermal and mechanical properties of the materials. V1.2 refers to Annex G of ENV 1994-1-2 [9], V2.0 refers to Annex H of EN 1994-1-2 [10]. V3.0 is based on buckling curves as described in EN 1994-1-2.

Versions V1.2 and V2.0 are based on the Guiaux-Janss method [1], which is used to define the axial buckling resistance $N_{fi,cr}$ for a column with different materials having non linear stress-strain curves at elevated temperatures. This load must be equal to the sum of the internal forces $N_{fi,Rd}$ existing at that moment.

$$N_{fi,Rd} = \sum \left(A_a . \sigma_{a,\theta} \right) \Big/ \gamma_{M,fi,a} + \sum \left(A_c . \sigma_{c,\theta} \right) \Big/ \gamma_{M,fi,c} + \sum \left(A_s . \sigma_{s,\theta} \right) \Big/ \gamma_{M,fi,s},$$ (1)

$$N_{fi,cr} = \pi^2 \left[\sum (E_{a,\theta.} I_a) + \sum (E_{c,\theta.} I_c) + \sum (E_{s,\theta.} I_s) / l^2{}_\theta \right],$$ (2)

where: $N_{fi,cr}$ is the critical or Euler buckling resistance; $N_{fi,Rd}$ is the sum of the internal forces on the total cross section; l_θ is the buckling length in the fire situation; $E_{i,\theta}$ is the tangent modulus of the stress-strain relationship for material i at temperature θ and for a stress $\sigma_{i,\theta}$; I_i is the second moment of area of material i, related to the central axis of the composite cross-section; A_i is the cross-section area of material I; $\sigma_{i,\theta}$ is the stress in material i at the temperature θ; $\gamma_{M,fi,i}$ is the partial safety factor in fire design for material i.

The design axial buckling resistance must be calculated step-by-step increasing progressively the deformation of the column, taking into account that the strains are equal in all materials, and obtained when:

$$N_{fi,cr} = N_{fi,Rd}.$$ (3)

When bending moments are present, i.e. when the column is eccentrically loaded, an equivalent axial load N_{equ} is calculated in such a way that the column will survive for the same time in fire when submitted to the real eccentrical load $N_{fi,Sd}$ and the fictitious axial load N_{equ} [10].

2.3. SAFIR computer code for the simulation of structural behaviour under fire conditions

SAFIR is a non-linear numerical code developed at the University of Liège [14]. It is especially devoted to the analysis of structures under elevated temperature conditions, although it can also be used to analyse structures under ambient conditions. The program, which is based on the Finite Element Method (FEM), can be used to study the behaviour of two and three-dimensional structures. SAFIR accommodates various elements for different idealizations, calculation procedures and material models incorporating stress-strain behaviour.

Two applications of SAFIR will be made in this article. They differ mainly by the models adopted for the material properties. The first one is made with the laws contained in ENV 1994-1-2 [9], while the second one is made with the laws contained in EN 1994-1-2 [10].

Using the program, the analysis of structures exposed to fire consists of two steps. The first step involves predicting the temperature distribution inside the structural members, referred to as "thermal analysis". The second step, named "structural analysis", is carried out in order to determine the mechanical response of the structure due to the thermal effects, since the load is usually assumed to remain constant during the fire.

The transient temperature field within a given network is established by a finite element method. It is assumed that conduction is the main heat transfer mechanism in the hollow steel section and concrete core. Convection and radiation act essentially as heat transfer from the fire environment to the external hollow steel section. The influence of moisture (assumed uniformly distributed in the concrete) is considered by modification of the specific heat.

The discretization of plane sections with different shapes is possible by using triangular and/or quadrilateral elements. For each element the material can be defined separately. Any material can be analysed provided its physical properties at elevated temperatures are known. The material properties are temperature dependent.

The meshing also affects the structural analysis because the same discretization is used. The integration of the longitudinal stresses and stiffness on the section is based on the fibre model, each finite element of the thermal analysis, with its known material type and temperature, is considered as a fibre.

Some other main characteristics of SAFIR are: the large displacement type element is in an updated corotational description, Bernoulli's hypothesis is considered, Von Karman's hypothesis is used: the strains are small, the rotations are assumed to be small, the longitudinal integrations are numerically calculated using Gauss'method.

3. COMPARISON BETWEEN THE THREE METHODS AND WITH EXPERIMENTAL RESULTS

3.1. Comparison between the three methods for classical values of the dimensions of the columns

In this first study two classical values of the diameter for circular cross sections have been chosen: 219.1 mm with $8\phi12$ and 406.3 mm with $8\phi20$. The load is applied centrically. The mechanical properties of the materials are: concrete, $f_{c28} = 25$ N/mm^2; hollow steel section, $f_y = 235$ N/mm^2; rebars, $f_y = 500$ N/mm^2. Two buckling lengths $L_b = 2$m and 4m have been considered so that the slenderness ratio of the columns can vary between low and high: sections 406.3 with $L_b = 2$ m have a low slenderness ratio, while sections 219.1 with $L_b = 4$ m have a high slenderness ratio. Four classical fire resistance times (30', 60', 90', 120') have been chosen. In this comparison the three versions of POTFIRE and the two material models in SAFIR have been used. For SAFIR, the value prescribed in Eurocode 4 for the accidental eccentricity ($L_b/300$) has been adopted.

The complete set of results is not reproduced here. Comparisons will be made from four diagrams (Fig 1a to d) corresponding to the values mentioned previously.

The results show that Kodur's formula is not applicable in many cases, which can be seen from the diagrams, as Kodur's results are not reproduced for various values of the fire resistance duration. This formula has several limitations [11, 12]: some are due to the fact that it cannot be applied beyond the experimental results on which it is based, other come from rules contained in Canadian standards. The

limitation involved here is related to the load applied on the column during the fire test. It is interesting to look more in detail at the implications of this non applicability for the two extreme cases: $\phi = 406.3 - L_b = 2$ m and $\phi = 219.1 - L_b = 4$ m.

For the wide section and $L_b = 2$ m, Kodur's formula is not applicable for the four values of R_f. The plastic crushing load under cold conditions $N_{pl, 20°C}$ is equal to 7 683 kN. If for example the values given by SAFIR EN94 are taken as references, the loading rate for the four values of the fire resistance are respectively 0.594, 0.407, 0.330 and 0.261. The first value is very high and will in practice never be reached, but the three other ones are medium or even low values. It is for example surprising to see that for $R_f = 120 - L_b = 2$ m, Kodur's method is not applicable. The value given by applying the formula is $N_{Kod} = 9\ 965$ kN, and is thus indeed completely unrealistic.

For the small section and $L_b = 4$ m, the plastic crushing load under cold conditions $N_{pl,20°C}$ is equal to 1 884 kN. Looking at the values given by SAFIR EN94, the following loading rates are obtained: 0.154, 0.088, 0.051, 0.026. In fact, for such a column, it is unrealistic to reach $R_f > 30$ min, even for a small loading rate, but $R_f = 30$ min is quite acceptable. But also in this case, Kodur's formula is not applicable.

For the values of the fire resistance durations considered in this study (up to 120 min), it can be observed that Kodur's method is not applicable for high loading rates, and in some cases also for medium and low loading rates. This is surely a serious limitation of the method, as the loads on most columns are rather high since the permanent loads are usually more important than the variable ones.

Let us now compare the results given by the three versions of POTFIRE. The first two are based on the determination of the buckling load, but the laws chosen for the mechanical properties of the materials are different. The results do not lead to clear conclusions. Version 3.0 like version 2.0 works with the mechanical properties presented in EN 1994-1-2 [10], but version 3.0 is based on buckling curves and therefore should give smaller values, since geometrical imperfections are integrated in the approach. This is the case for most results, but not for all of them.
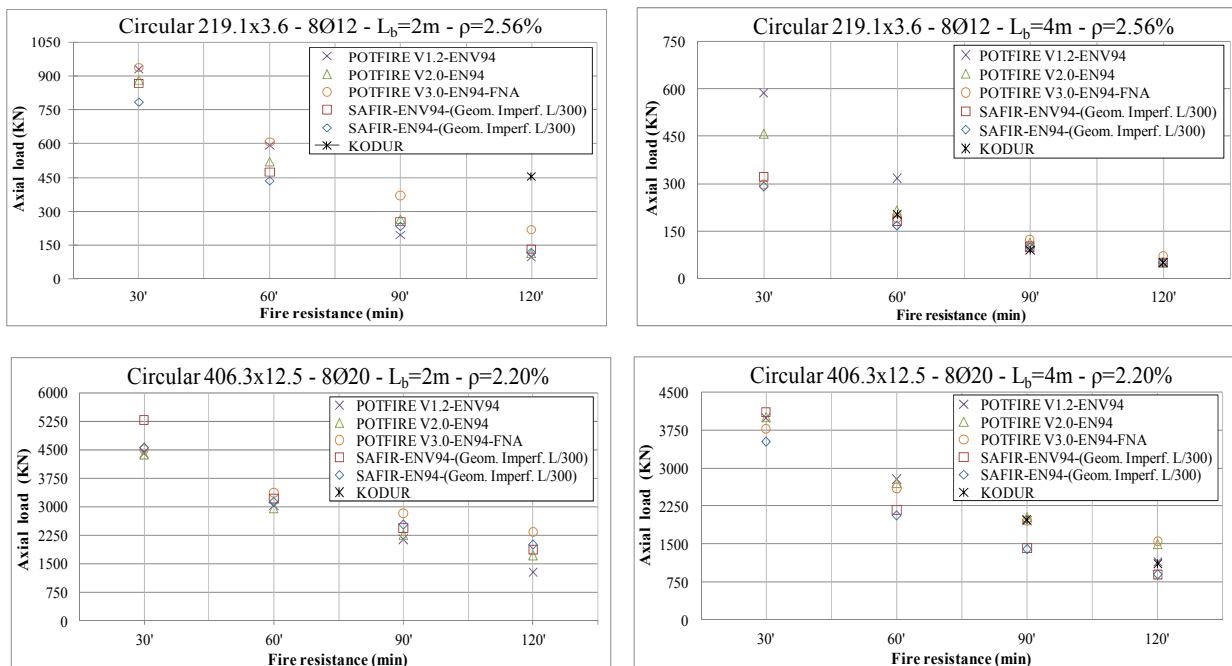

Fig.1 – Comparison between the results of the different methods for four particular cases.

The two applications of SAFIR give rather close results, but the one based on EN94 leads generally to smaller values.

It is also interesting to compare the two more recent versions of POTFIRE and SAFIR, both taking into account geometrical imperfections. It can be seen that the results given by SAFIR are lower than those given by POTFIRE.

3.2. Comparison between the results of the three methods and experimental results.

In order to analyse further the results of the three methods, these have been compared with test results obtained in various laboratories and described in detail in [2, 3].

All columns are centrically loaded. All sections are square $260 \times 260 \times 6.3$ mm with reinforcement ratios of 0 (plain concrete), 1 and 2% approximately. The load applied is 800 kN in the case of plain concrete and 1 500 kN for concrete with rebars.

All the columns presented here have a total length $L_t = 3.60$ m. The loading device is given in Fig 2. The columns are not hinged and a partial rotational restraint exists at both ends, which is rather difficult to evaluate. In [2] some considerations have led the author to adopt $L_b = 0.7 \ L_t$ though he admits that there is some indetermination on this parameter. This value has also been adopted in this study.

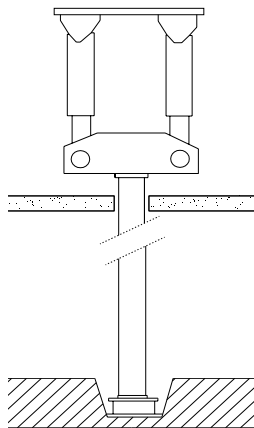The results are presented in Fig. 3. All are on the safe side, except two from Kodur.
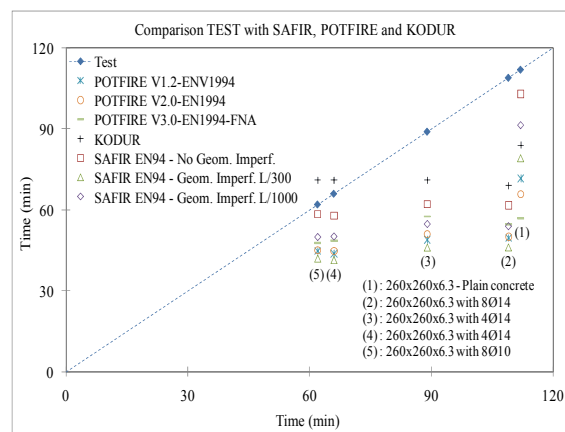

Fig. 2 – Loading device.

Fig. 3 – Comparison between the test results and the models.

Concerning SAFIR results, only the most recent version of the material properties has been used, but three values of the geometrical imperfections have been considered. Though the columns are centrically loaded, there always exists a geometrical imperfection, and the evaluation of the fire resistance on the basis of the crushing load is somewhat on the unsafe side. On the other hand considering an imperfection $L/300$ like the one recommended in EN 1994-1-2 [10] might be too much on the safe side. From observations made during tests performed at the University of Liège on rather similar types of profiles, it has been concluded that the real imperfections are very small [15]. Therefore calculations with an imperfection $L/1000$ have also been performed, and this should be considered as the most appropriate assumption for the simulation.

For POTFIRE, the three versions have been used. Versions V1.2 and V2.0 give results close to each other. For version V3.0 the values differ. The difference is particularly important for the case plain concrete: V3.0 gives smaller values since geometrical imperfections are taken into account. When rebars are present, the differences are small.

Concerning Kodur's method the values are closer to experimental results, but it can be noticed that two values are higher than experimental results, the difference being significant in one case (close to 15 %).

Kodur's formula's have been obtained from a calibration with 58 test results. Almost all (54 out of 58) have been made with fixed end conditions, and it is well-known that in this case high values of the fire resistance time are obtained, as the influence of geometrical imperfections is negligible. This explains why on one side results given by Kodur may be rather close to experimental ones. On the other side they may be unsafe when applied to columns hinged or with partial restraints at both ends, where geometrical imperfections may have a significant effect.

It can be seen that the most significant values of SAFIR and POTFIRE (SAFIR – EN94 – L/1000 and POTFIRE V3.0) are close to each other. The models apparently do not capture the increase of fire resistance that is observed in the tests by an increase of the sectional area of the bars.

3.3. Comparison between the results of two methods for eccentrical loads

In the two preceding comparisons the columns were centrically loaded. It has been found interesting to compare the methods for eccentrical loads. To this aim the circular section 323.9 with 8 ϕ 16 has been examined using SAFIR with one material model and two versions of POTFIRE. Three values of the eccentricity have been chosen: 10, 20 and 50 mm. The calculations have been performed (Figs. 4 and 5) for two values of the buckling length: L_b = 1 and 4.5 m (low and high slenderness ratios).

Kodur's formula's are not applicable, as in this method the column has to be axially loaded. Versions V1.2 and V2.0 of POTFIRE have been used because it was not possible to introduce an eccentricity with version V3.0. Concerning SAFIR, no geometrical imperfection has been taken into account. It is assumed that it is covered by the external eccentricity.

Fig. 4.a to c correspond to the case L_b = 1 m, i.e. a column with a small slenderness ratio. The diagrams show that the two versions of POTFIRE give results close to each other, while the values given by SAFIR are appreciably higher. This is true for all values of the fire resistance time, and for the three values of the eccentricity.

The case L_b = 4.5 m is displayed in Fig. 5.a to c and corresponds to a high slenderness ratio. It can be seen that the results given here by the three approaches are rather similar, except for very small values of R_f corresponding to high loads. The same observation can be made for the three values of the eccentricity.

To explain these differences the following considerations could give some indications. SAFIR and POTFIRE do not work in the same way. SAFIR is a numerical code that simulates the behaviour of the structural element up to failure. POTFIRE has first been established for centrically loaded columns on the basis of the buckling load. For eccentrical loads the procedure proposed is somewhat artificial. It consists of replacing the eccentrical load by a centrical one affected by a coefficient of correction in which only three parameters are considered: the eccentricity, the slenderness and the percentage of steel. However, other factors not taken into account may influence the effect of eccentricity, e.g. the concrete strength, the concrete cover to the bar reinforcement, and therefore the accuracy of the coefficient of correction may not be the same for all cases.

4. CONCLUSION

The following conclusion can be drawn from this research study.

Kodur's formula's are easy to use; they are empirical, but they have been established on the basis of many tests and numerical parametric studies; the values calculated are rather close to experimental results.

On the other hand, the method is applicable only for axial loads; the formula's have several limitations, one of the most important being the fact that they are not applicable for certain loading rates (mainly high); the method gives the same result within a rather wide range of percentage of reinforcement; the values calculated are based mainly on tests with fixed end conditions, therefore they can be unsafe in some cases when applied to columns with other end conditions.

POTFIRE is easy to use; it can be applied to centrical and eccentrical loads; circular, square and rectangular cross-sections can be treated.

On the other hand, the method is based on the evaluation of the buckling load, and therefore cannot take into account an accidental eccentricity for axial loads; for eccentrical loads, the procedure proposed is somewhat artificial, and the coefficient of correction proposed could be improved for some situations.

SAFIR is a non-linear computer code that can simulate the behaviour of structures under fire conditions, and therefore it can provide many informations; the program can treat not only isolated columns but also more complete structures such as moment resisting frames under various loading and boundary conditions; for axial loads, it is possible to introduce an accidental eccentricity, the value (L/1000) appearing the most realistic for the type of profile examined here.

On the other hand, the code is rather easy to use, but some practice is necessary before applying it extensively; SAFIR provides the fire resistance duration, but to get the maximum admissible load for a given fire resistance time, it is necessary to proceed step by step.
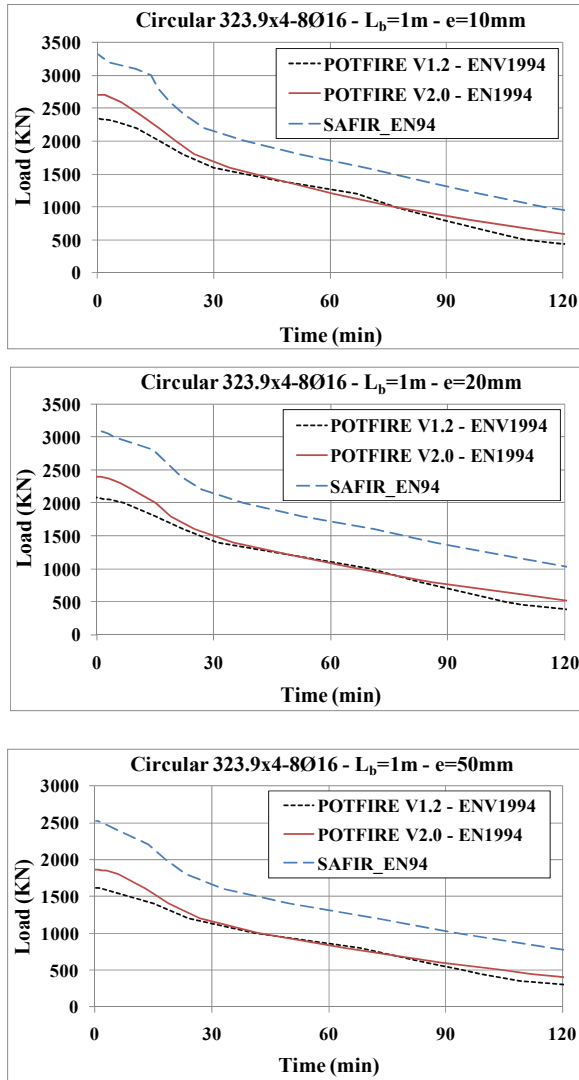
Fig. 4 – Comparison between two methods for eccentrical loads
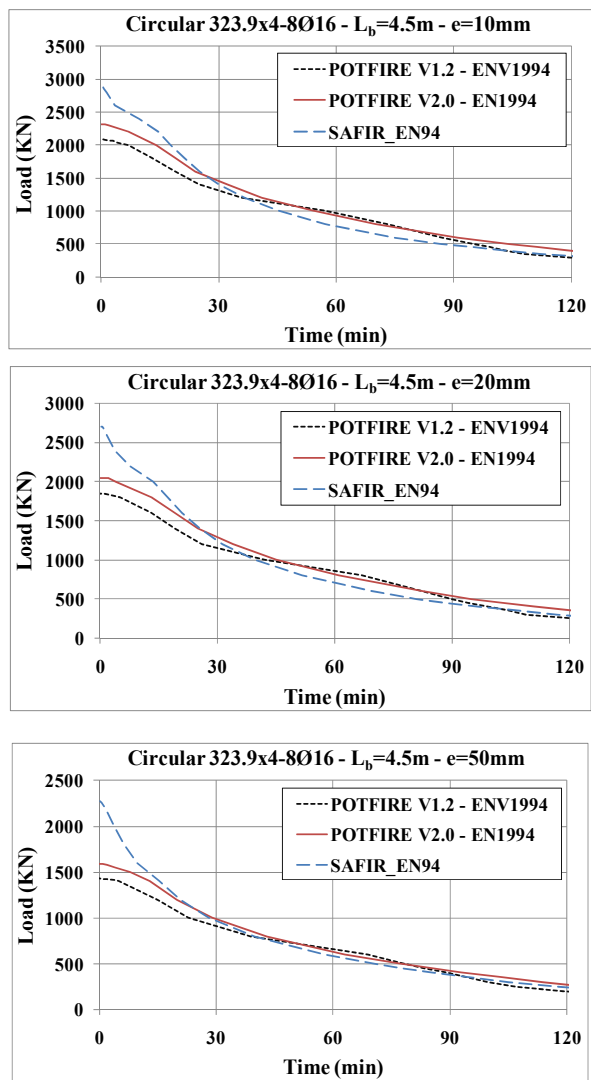and $0 < R_f < 120$ min – $L_b = 1$ m.

Fig. 5 – Comparison between two methods for eccentrical loads
and $0 < R_f < 120$ min – $L_b = 4.5$ m.

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