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RESIDUAL STRESSES IN STEEL PROFILES SUBMITTED TO THE FIRE: AN ANALOGY

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I. THE INTRODUCTION.

The process of hot rolling steel profiles leads to residual stresses in the section. The distribution of those residual stresses has been widely investigated and standard distributions have been proposed, depending on the geometrical characteristics of the section [1].

When the profile is submitted to a fire, the evolution of the residual stresses is not very well known and their influence is not always considered appropriately in the calculation. The simplified method totally disregard them for bending situation and when it comes to buckling, it is usually recommended in Europe to adopt the buckling curve c supposed to be valid at elevated temperatures for any kind of section [2]. The situation does not seem very clear either in the numerical codes that have been written for the simulation of the behaviour of steel frames in fire. Most of them ignore the residual stresses. Some others take the opposite position, i.e. that the residual stresses remain constant during the fire as it seems to be the case for Culver et al. [3, 4, 5]. Some others like Aribert [6] have an intermediate position which they do not justify ; the residual stresses decrease with temperature in the same manner as the yield strength does.

This paper explains via an analogy what the residual stresses are and what they are not. It explains the solution that has been adopted for several years in the code CEFICOSS [7, 8] and, more recently, in the code SAFIR at the university of Liège. Finally, some indications are given concerning the influence of the residual stresses on the fire resistance of steel structures.

II. THE ANALOGY.

Let us consider a paratrooper jumping from a balloon (Fig. 1). There is no wind and he leaves the balloon vertically so that the movement is uniaxial (vertical in this case). Two forces are leading the movement ; the gravity and the resistance to the penetration in the air. All naturally, we are going to set time = 0 at the moment when the man leaves the balloon. The differential equation can be written and solved. Fig. 2, for example, is a graphical presentation of the evolution of speed (S_1) as a function of time. At the origin, the initial speed is equal to zero, as well as the resistance. The speed is increased by gravity and, later on, there is a tendency to reach a steady state condition where the resistance is equal to gravity (Sy on Fig. 2).

Unfortunately, this man is not lucky and his parachute does not open. After a certain period of time he reaches the ground, which is for him equivalent to failure. We could

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calculate that the area under the curve of speed is equal to the altitude of the balloon.

Now there is a second paratrooper in the balloon who is a little bit reluctant to jump because he is not happy with what he saw and he must be pushed out by the officer. Let us assume that the officer pushes him mainly vertically and downward, in order to keep the movement uniaxial.

Are we going to declare time = 0 at the moment when the officer begins to push ? That would oblige us to first calculate the movement S_2 when it is very difficult and involves a lot of parameters ; the mass of the paratrooper, the mass of the officer, the length of his arm, the power of his muscles, the position of his hand in the back of the soldier, ... The equations are also very complicated, up to the moment when the paratrooper leaves the balloon, assimilated to the moment when the officer stops to push (t_i on Fig. 3). From this time, the movement S_2 is ruled by the same two forces and the same equation as was s_1.

No, we are not going to do that. We are going to measure the speed S_i of the paratrooper at the moment t_i when he leaves the balloon. Or we will rely on other people who have made it for us. We know that the average paratrooper, when pushed by the characteristic officer, leaves the balloon at a speed the mean value of which is, say, $S_i = 0{,}3 \times S_y$. We are then going to set t = 0 at this moment when he leaves the balloon and use the same set of equations as to calculate S_1. The only difference is that we have now to consider an initial value of the speed which is not equal to zero (see Fig. 4).

We are able to calculate S_2 (the speed of the movement with an initial value) and to compare it to S_1 (the speed of the movement with no initial value). We can, at any time t, compare S_2 and S_1 and evaluate the influence of the initial condition S_i on the speed. But by no means can we declare that the difference ΔS is what the initial speed has become. The initial speed becomes nothing. It is only meaningful at time t = 0, after which it stops to exist and only its effects can be observed. We can also evaluate the influence of the initial speed on the failure time (this is a bad day for the army and this parachute does not function either) and that is the most important, from the engineering point of view (if not from the point of view of the paratrooper).

The situation is exactly the same if S represents the stress in a steel profile instead of the speed of a poor man falling from the sky. If we suppose that the steel industry is able to provide us with profiles that are totally free of stress, we are going to set t = 0 at a moment when the profile is unloaded and unheated. We are then going to apply our set of equations (equilibrium, compatibility, ...) to calculate the evolution of the stress S_1 as a function of time and, eventually, the fire resistance.

If now, we realise that stresses are already present in the profile prior to the loading and the heating, what are we going to do ? Are we going to declare time = 0 and to calculate what happened to steel since the big bang, during the geological ages of mother earth, during the extraction of the raw material, during the melting of steel, during the rolling of the profile and its cooling down ? No, we are not going to do that because the equations are too complicated and involve much too many parameters. We are going to measure the stress at the moment that would be convenient to be declared as t = 0 ; just before the loading and the heating. Or we are going to rely on people who have done it for us and we know that the ordinary steel section, rolled by usual means, has stresses that can be as high as, say, 0,3 x σ_y. We can now calculate the evolution of stress during the loading and the heating by the same set of equations as to calculate S_1. The difference is that we have now to consider an initial value of the stress. Of course, we use to call it a residual stress to indicate that it is a residuary of the past. But, when it comes to calculation, this must really be considered as an initial value. We can compare the stress S_2 calculated with a residual stress (i.e. an initial stress) and the stress S_1 calculated when the residual stress is neglected but by no means can we declare that the difference is what the residual stress has become. The residual stress does not become anything. It is only the value of the stress at the time that we have decided to declare as t = 0. Period. Of course, weather this initial stress has a significant influence on the final resistance of the structure is the real question to which we should be able to answer.

"O.K. Well" do I hear you think (yes, I can really hear you think). "The story is pleasant but what I know for sure is that when a steel profile full of residual stress is heated and then cooled down slowly, at the end of the day, the residual stresses have vanished. Isn't it an experimental proof that the residual stress do evaluate and become equal to zero ?"

I say "no". This is the story of another paratrooper who, believe it or not, must also be pushed out of the balloon so that he leaves it (at time t = 0) also with an initial value of the speed. This one is yet luckier and his parachute opens so that the speed is decreased (see S_3 on Fig. 5). He reaches the ground quite softly and having been submitted to much less severe conditions, he manages to survive. He enjoyed the experience so much that he decides to do it one more time and climbs on the rope to the basket. There is now no need to push him and he leaves the balloon with no initial speed. If we want to calculate the movement for this second jump, we are not going to consider all that happened during the first jump of this man. It would be too complicated and totally uninteresting. We are going to change the origin of time and declare time = 0 at the beginning of the second jump. It is so simple.

The situation is the same for a steel profile that has residual stresses. We heat it up unloaded and let it cool down slowly. The environment is much less severe and it does not reach failure. Creep and plasticity can play their role and indeed at the end of the day the stress has become equal to zero, whereas the initial stress has not become anything. If now we want to analyse what becomes to this profile when it is loaded at ambient temperature ant then submitted to a fire, we are all naturally going to declare t = 0 just before the loading and totally disregard what happened during the stress relieving process, except that for this new calculation, we will consider a null initial value of the stress, i.e. a null residual stress.

III. THE EQUATION.

We are interested in the evolution of the stresses in the structure during the loading and the heating. For every point of the structure we could write (provided that a uniaxial stress distribution is assumed).

$$\sigma = \sigma_i + \Delta\sigma \qquad \text{(eq. 1)}$$

where

σ	stress
σ_i	initial (i.e. residual) stress
$\Delta\sigma$	variation of the stress from the state of reference, i.e. from t = 0.

This equation cannot be used practically because the material behaviour is highly non linear and the stresses cannot be added. It is better to write the material law in terms of strains.

$$\varepsilon = \varepsilon_i + \varepsilon_{th} + \varepsilon_\sigma + \varepsilon_{cr} \qquad \text{(eq. 2)}$$

where

ε	is the real strain linked to the field of displacements
ε_i	is the initial strain. It is defined as the strain that would show up if, at the state of reference, the material at this point could be released from any link with the rest of the structure. Such a strain is therefore defined at each point of the structure once the state of reference has been chosen and **it will not change anymore.**
ε_{cr}	is the creep strain
ε_{th}	is the thermal strain (due to the thermal elongation)

ε_σ is the part of the real strain that is available to induce stresses (stress related strain).

The definition of ε_i is used for the experimental determination of the residual stress when from the state of reference (unloaded and unheated) a profile is cut in small bars which amounts to isolate different points from the rest of the structure. The elongation U is measured and ε_i is calculated as $\varepsilon_i = U/L$, with L the length of the bar. The strain is multiplied by the young modulus to obtain a stress $\sigma_r = E.\varepsilon_i$. In fact, a measured elongation means that there was compression in the section and the residual stress is calculated as $\sigma_r = -E.\varepsilon_i$. Eq.2 provides the same result because $\varepsilon = 0$ at the state of reference (by definition), as well as ε_{cr} and ε_{th}. Eq.2 yields $\varepsilon_\sigma = -\varepsilon_i$ and, if the material has still a proportional behaviour for this stress level

$$\sigma_i = E.\varepsilon_\sigma = -E.\varepsilon_i \qquad \text{(eq. 3)}$$

IV. THE INFLUENCE.

Elementary calculations show that a residual stress distribution with maximum values of 0,5 x 235 MPa is equivalent to a non uniform temperature distribution with maximum differences of about 110°C.

It can also be shown [9] that as long as the material remains elastic and the structure has no geometrical second order effect, the stresses in an unrestrained structure that is uniformly heated vary in the same manner as the Young modulus. This fact, combined with the fact that the Young modulus and the yield strength vary in a similar way when the temperature increases, explain why the choice made by Aribert [6] is a good approximation. When the material enters the non linear domain, no direct link can be made between the evolution of the stress and the evolution of any of the parameters which describe the stress-strain relationship.

When the equation 2 is used in a numerical code (SAFIR, developed at the University of Liège) to simulate the behaviour of a simply supported beam, with and then without any residual stresses, there is a very limited difference concerning the mid span deflection in the moments just before the collapse. This difference is yet so small that it can hardly be noticed on a drawing. There is no difference concerning the final fire resistance, which is also predicted by the theory of plasticity.

Residual stresses are the most sensitive when it comes to the simulation of axially loaded columns. Fig. 6 shows the buckling curves calculated for one profile with and without residual stresses, when the section has the uniform failure temperature of 20°C, 400°C and 700°C. The material laws are chosen according to Eurocode 3 [10]. This drawing indicates that there is an influence on the buckling load. The relative difference tends to decrease as the temperature increases especially for short columns. Fig. 7 shows that the difference is reduced when the load is applied with an eccentricity, i.e. when the situation is moving from pure buckling in the direction of pure bending. As an order of magnitude, it can be remembered that the influence of the residual stresses is almost annihilated when the eccentricity of the load in the section is higher than the radius of gyration of that section.

An experimental investigation has been made concerning the influence of the residual stresses on the fire resistance of beams [11]. It confirmed the fact that this influence is small. It would yet be scientifically incorrect to pretend that the results validated the model that is presented here because, although the results of the simulations where good, good correlation could probably also be obtained in this case with different models due to the low sensitivity of beams to residual stresses. Another research project is running for the moment, the experimental phase of it consisting on buckling tests on the same section (HE 100A) with a low eccentricity (5 mm.) and different lengths (510 to 4020 mm.).

V. THE CONCLUSIONS.

Residual stresses must be considered as initial stresses and modelled as such, which is particularly easy to do, theoretically and numerically.

In plane frames discretized and calculated as made of beams, the residual stresses have a significant influence mainly in the case of axially loaded columns. They can therefore be ignored in the case of frames with rigid connections, where all the elements are submitted to a significant degree of bending.

The residual stresses should probably be of more importance in structures that are discretized and calculated as an assembly of plate elements. We think of the analysis of local buckling in the steel profiles for instance. In this situation the plates which form the flanges are submitted mainly to membrane forces and their lateral buckling might well be sensitive to the presence of residual stresses. The philosophy that has been presented here for the discretization could also be used in this case.

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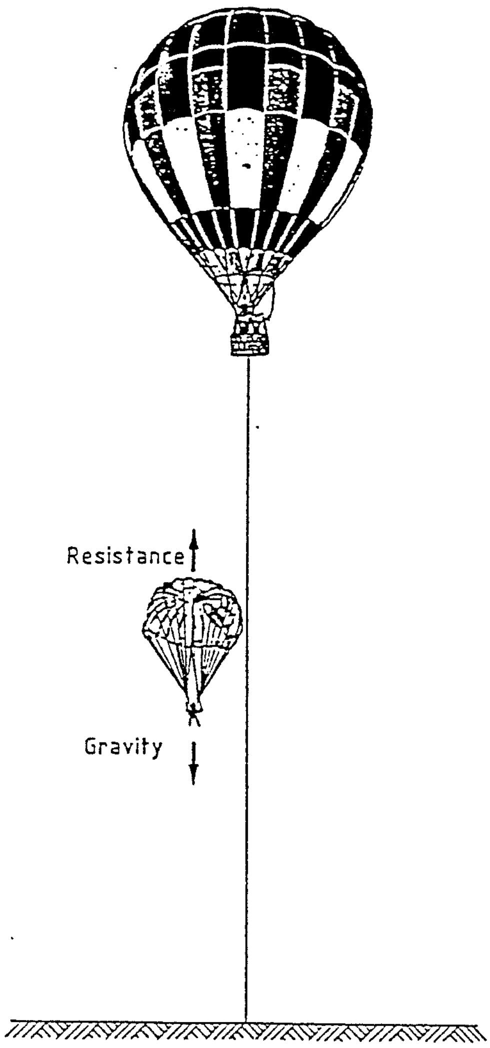

Fig. 1

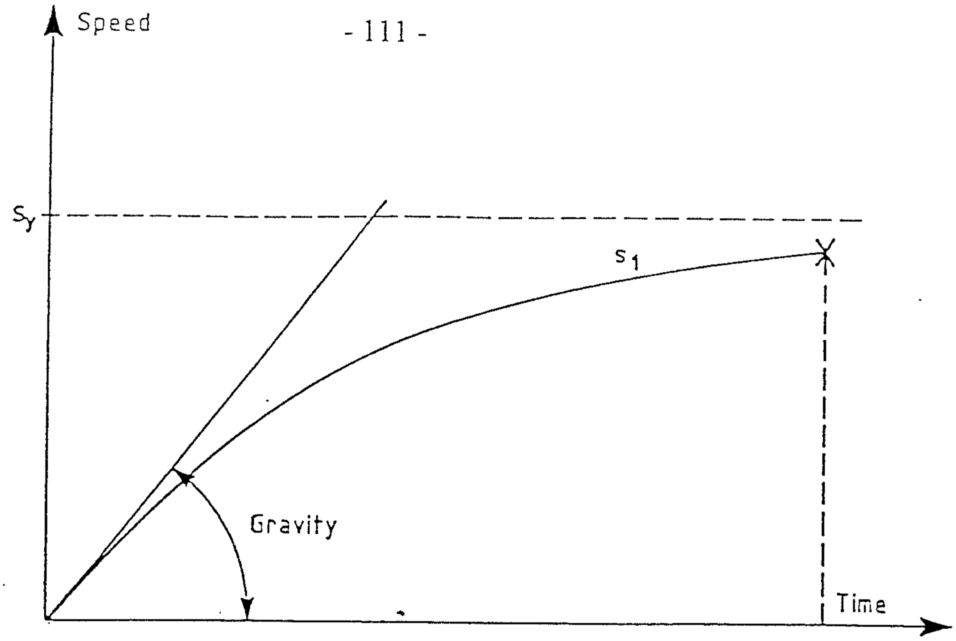

Fig. 2

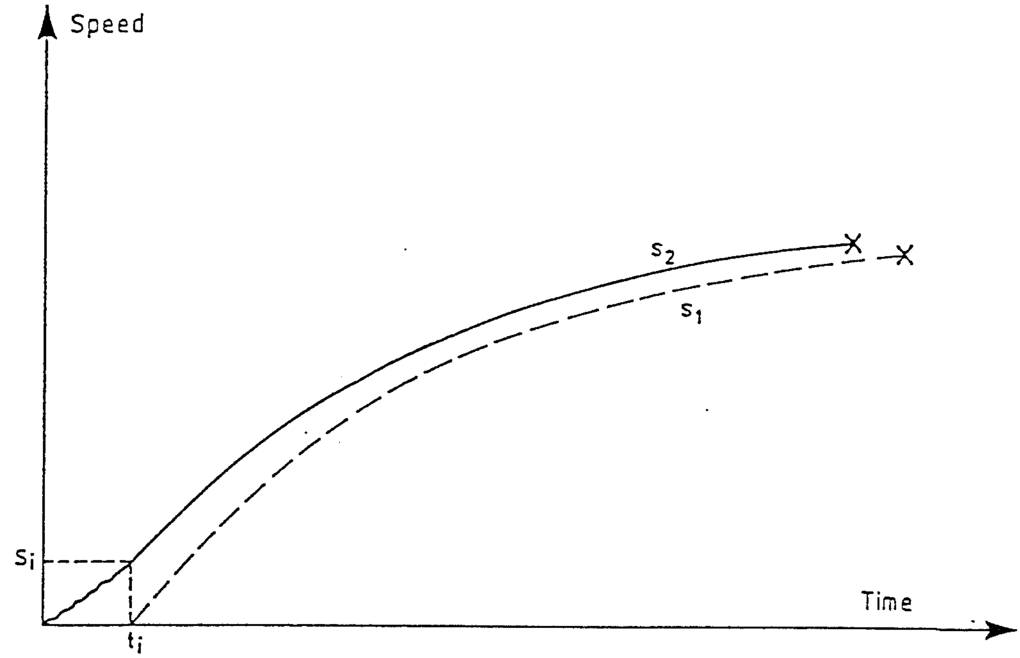

Fig. 3

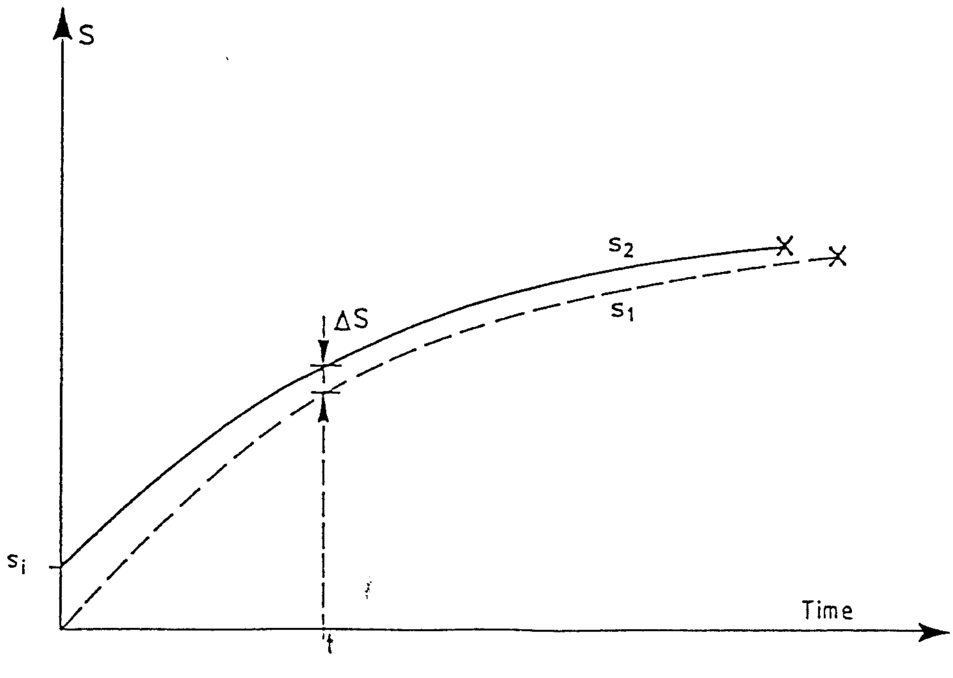

Fig. 4

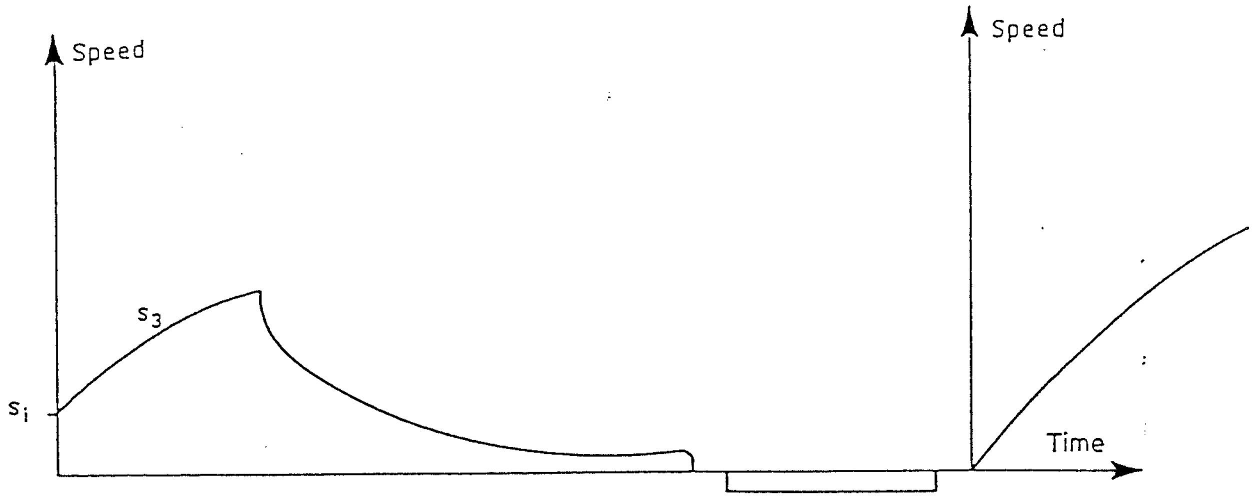

Fig. 5

HE100A 235 MPa Weak axis (SAFIR calculations)

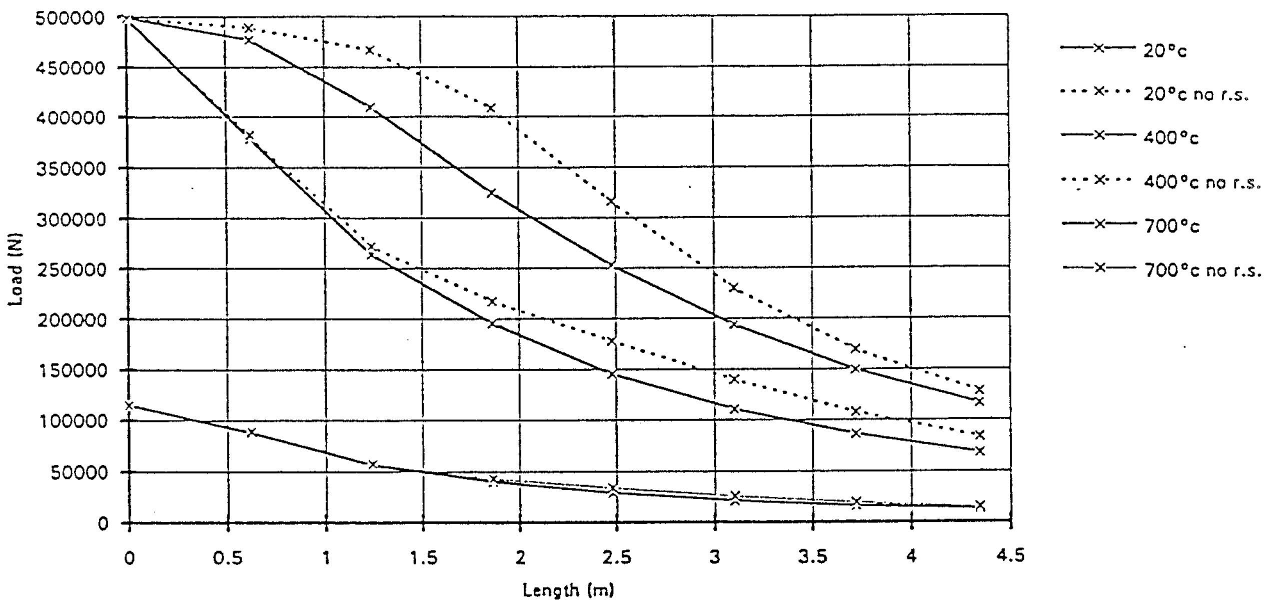

Fig. 6

HE200B, Weak axis, Tu = 500°C, H = 5 m

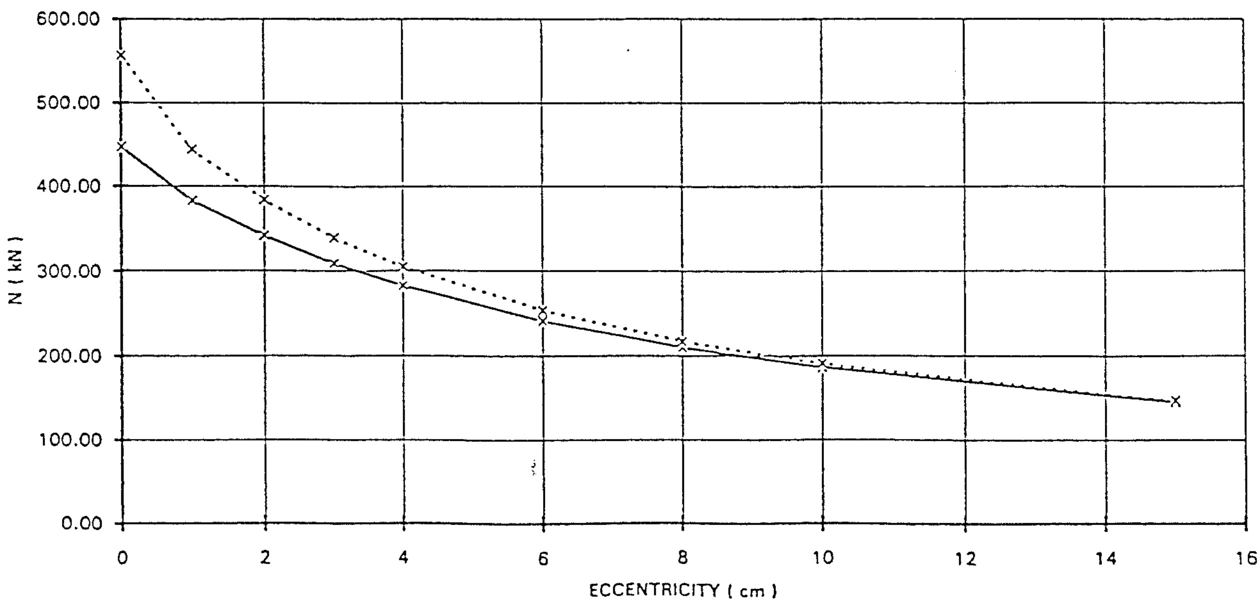

Fig. 7