Fire Safety Analysis

Examples with PowerFrame

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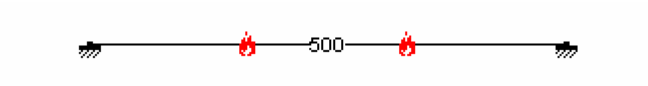
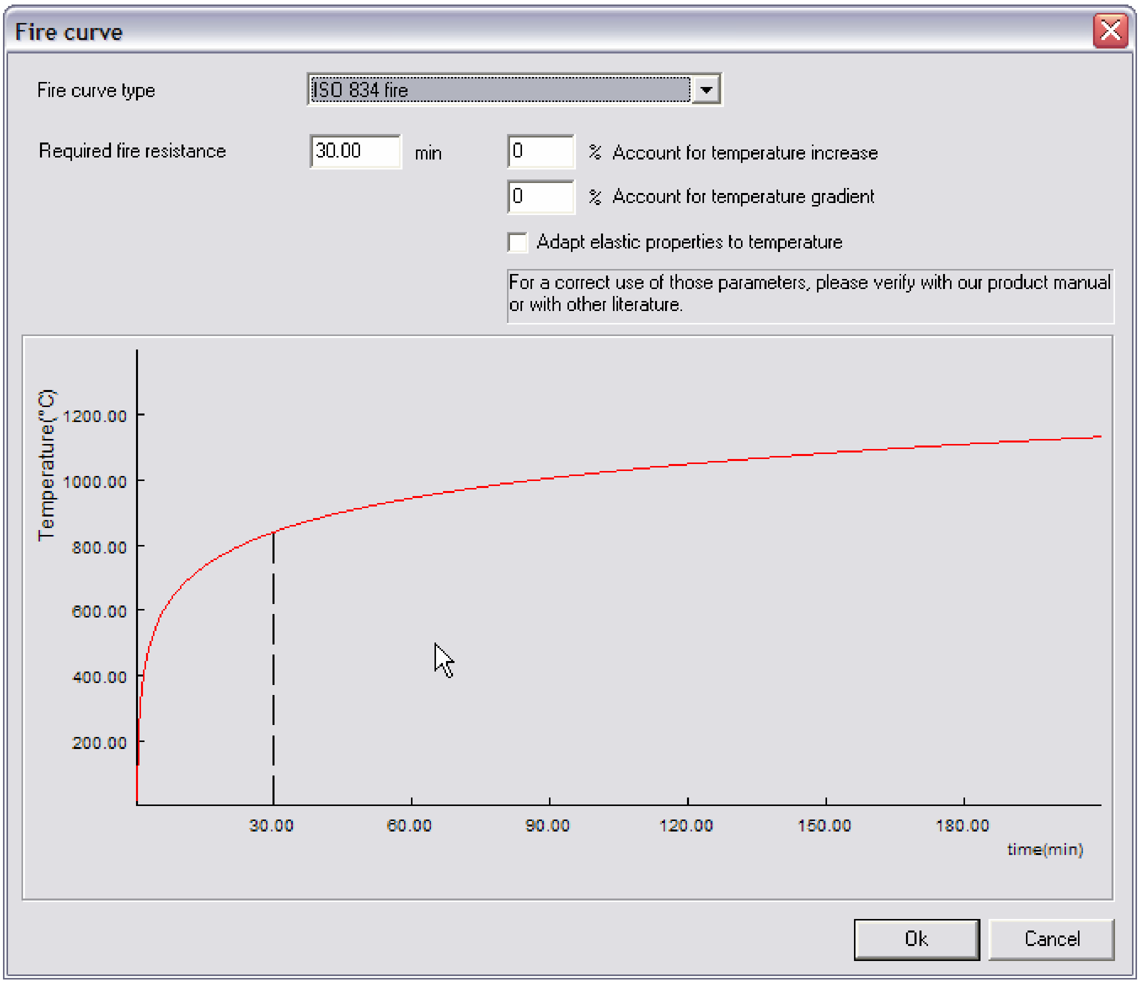
2 Examples

The use of the PowerFrame Fire module will be illustrated through the example below. Consider a beam element of 5m, fully clamped at the left and the right. Next to its selfweigth, this beam is loaded by a permanent load of 30 kN/m and a life load of 50 kN/m.



It is requested that this beam element will maintain its load carrying function for at least 30 minutes during a fire hazard. No extra information is available on the room adjacent to the beam element, so it is assumed that a standard ISO834 fire model can be applied.



The standard design method will be used, implying that internal forces related to non-uniform temperature variations will not be considered. Furthermore, the elastic analysis for the ULS Fire combinations will be based on the initial stiffness characteristics (at room temperature conditions). For the accidental load combinations, only the quasi-permanent part of the variable loads (ψ_2) is taken into account.

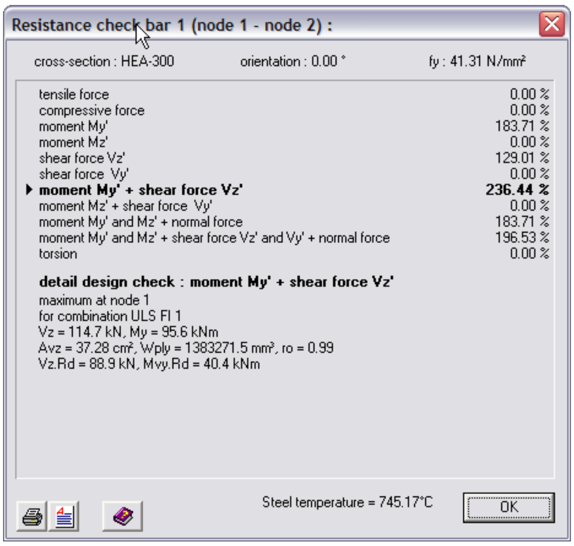
Let us now briefly discuss the thermal and mechanical response of this beam for a number of typical cross-section types.

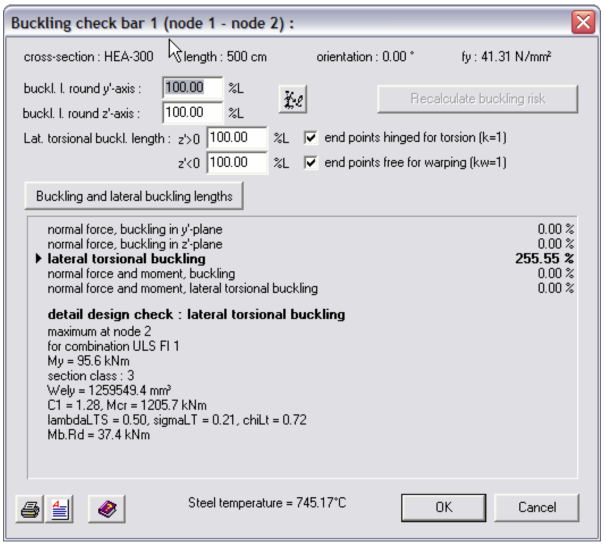
2.1 Unprotected HEA section

2.1.1 Exposed to fire at all sides

A HEA 300 section is considered, without any particular fire protection. An elastic analysis and design check at room temperature conditions shows that this type of section is the most economic choice for the given span and loads. Considering however the high thermal conductivity of steel, it is expected that the element will fail very soon once the fire begins to develop.

Due to the temperature increase (ΔT = 725,2 ℃ after 30 minutes), the yield strength will be reduced tot 41,3 N/mm^2. Using this reduced property, a code check can be performed with respect to Eurocode 3. The results are given below:





Despite the fact that a HEA 300 is perfectly capable to resist the above loads in normal room temperature conditions, it is not capable to maintain its function during a fire hazard. This should not be a major surprise, considering the temperature increase and the related deterioration of material characteristics.

The resistance and buckling verification of a structural element subject to a fire load is performed in exactly the same way as for room temperature conditions, except for the following items:

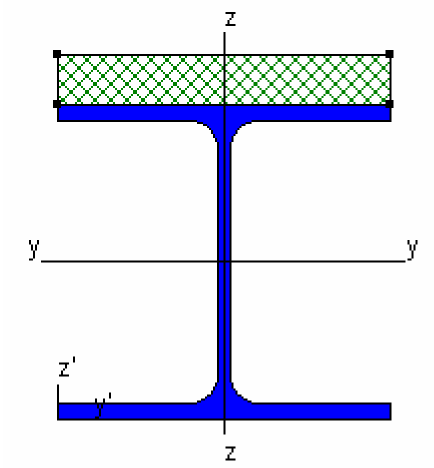
- the cross-section classification is done using reduced mechanical properties. Approximately, the classification is done using a value of $\varepsilon = 0.85\sqrt{235 / f_y}$;
- relative slenderness values are based on mechanical properties for 20℃. Those values are however to be corrected by a multiplication factor $\sqrt{k_{y,\theta} / k_{E,\theta}}$;
- imperfection factors for buckling and lateral torsional buckling calculations are determined using a value of $\alpha = 0{,}65\sqrt{235 / f_y}$;
- for Class 1, 2 & 3 sections, the reduced yield strength is introduced into the code checks;
- for Class 4 sections, the effective section characteristics (to be used in the verification formulae) are based on mechanical properties for 20℃. The yield strength should however be replaced by the reduced 0.2% strain limit $f_{p0,2,\theta}$.

2.1.2 Exposed to fire along 3 sides only

It was previously assumed that all 4 sides of the steel section were exposed to fire. Let us now consider the situation in which no heat transfer is possible along the upper side of the HEA section. To define such a thermal boundary conditions in PowerFrame, the section should be taken into Section Utility and the upper surface should be coupled to a fire buffer. Such a fire buffer should be considered as a material with infinitely low thermal conductivity. Inside Section Utility, you should proceed as follows:

- draw a rectangular section with arbitrary dimensions, adjancent to the upper surface of the steel section.
- double-click on the newly defined rectangle and select the second tab page ‘Material’.
- select the material ‘Fire buffer’ from the list of materials. Leave the default material ‘Staal(Fe360)’ unchanged.

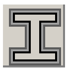
The drawing will now look as follows:

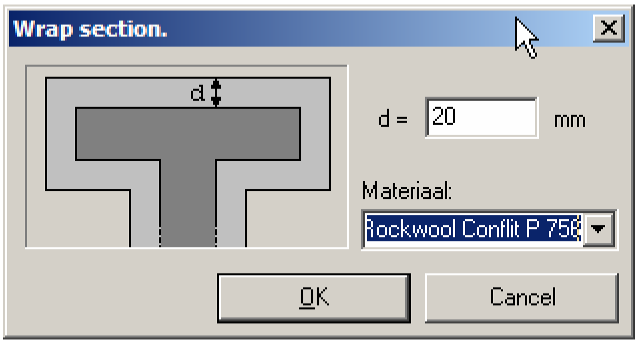


Take this section back to PowerFrame, click on the -icon and complete the resistance and buckling verification. You will notice that the fire buffer will only have minor impact on the analysis results. This is easily explained by the fact that steel temperature after 30 minutes is still at 733,9℃.

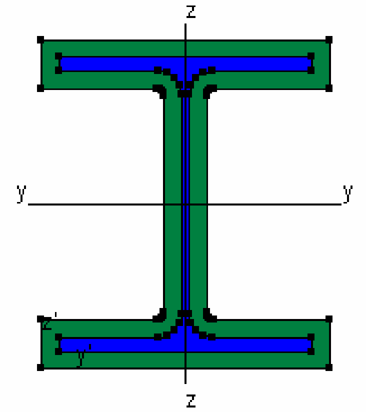
2.2 Protected HEA section

Let us now look at the case of the same HEA 300 section, but protected by a thermal insulation material. To define this, let's open Section Utility and wrap the entire section by an insulation layer (Rockwool Conflit P 756, thickness 2cm).

Select the entire section using the left mouse button and then click on the  icon to open the following dialogue window:

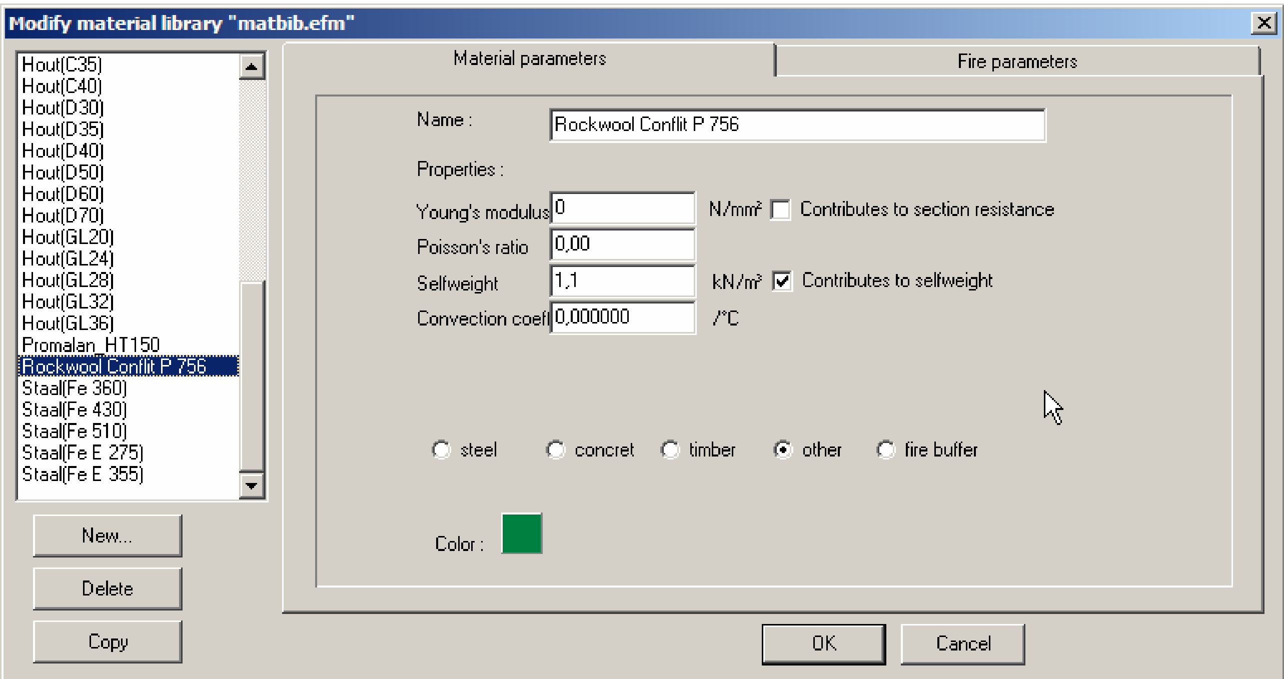


Specify the insulation layer's thickness and select the appropriate material. The section should now look like this:



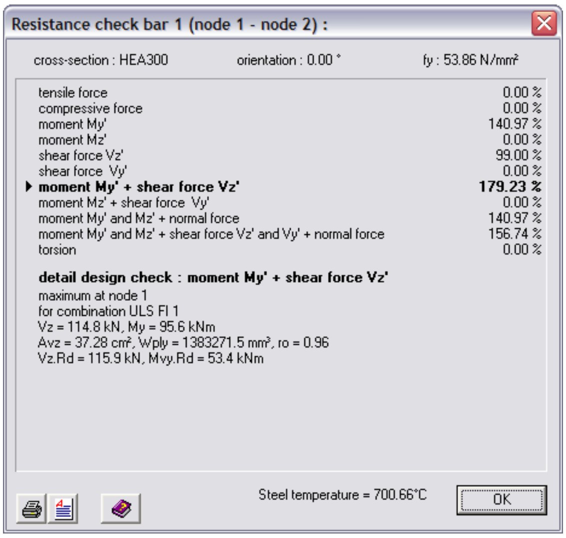
Remarks:

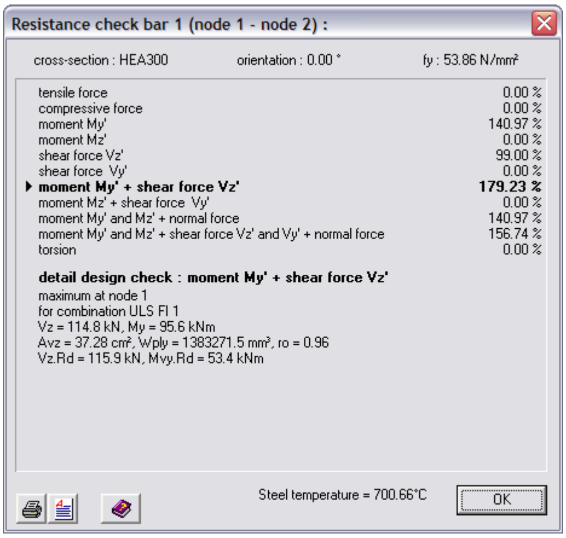
- Notice that the cross-section properties remain unaffected by this insulation layer, except for the self weight. Indeed, the insulation layer does not have any contribution whatsoever to the section's stiffness properties.



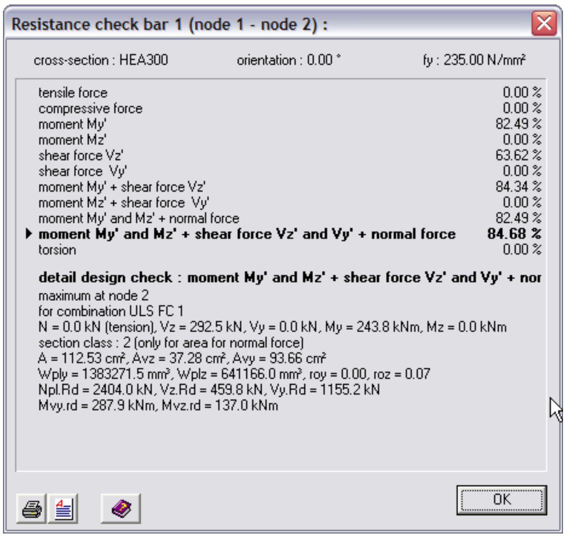
- Before the insulation layer is added to the section, we could have declared the HEA section to be deformable. In this case, PowerFrame will consider the section as a composite one and no longer as a protected steel section. Consequently, the thermal analyses will be done by the Physibel thermal solver for arbitrary cross-section types.
- In case an insulation layer with variable thickness is defined, the section's temperature variations will also be calculated by the Physibel thermal solver.

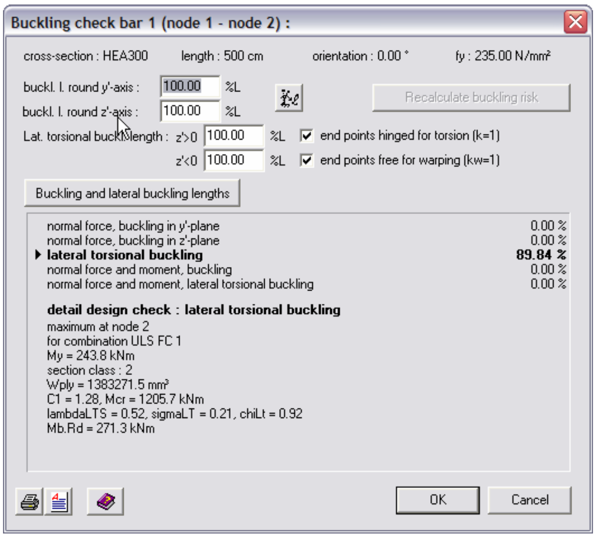
It can be observed from the results below that the insulation layer does not dramatically improve the fire resistance of the steel beam. Steel temperature is only about 45°C lower compared to the unprotected steel section.





This is not a surprising conclusion, as such type of insulation material will start to loose its insulation capacity from 400°C onwards. This type of material is therefore not inappropriate when severe fire resistance demands are to be met. In case a different material is selected (gypsum) of which the thermal conductivity only increases slightly with higher temperatures, it can be observed that steel temperatures will be significantly lower than steel temperatures for an unprotected section.



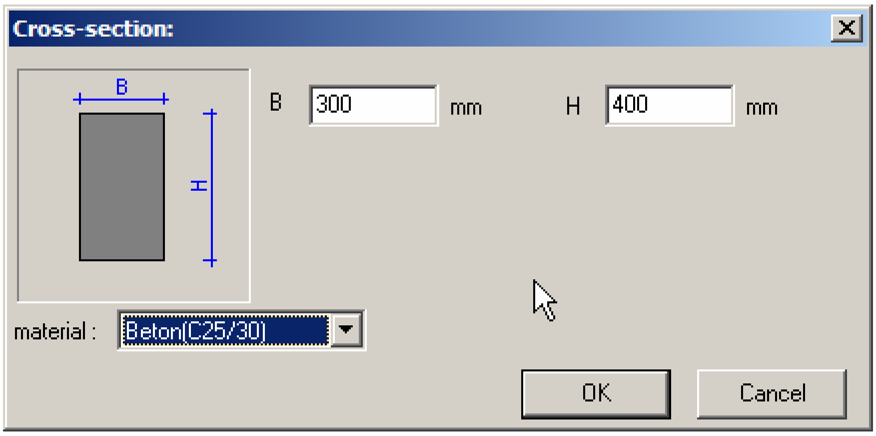


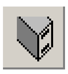
At those temperatures, yield strength will only have decreased to a moderate extent, in contrast to Young's modulus, or will even remain at the initial value of 235 N/mm^2. Therefore, the analysis results will not differ significantly from the ones performed at room temperature conditions. This is confirmed by the above dialogue windows, which indicate that the ULS FC 1 is a more critical combination than the fire combination.

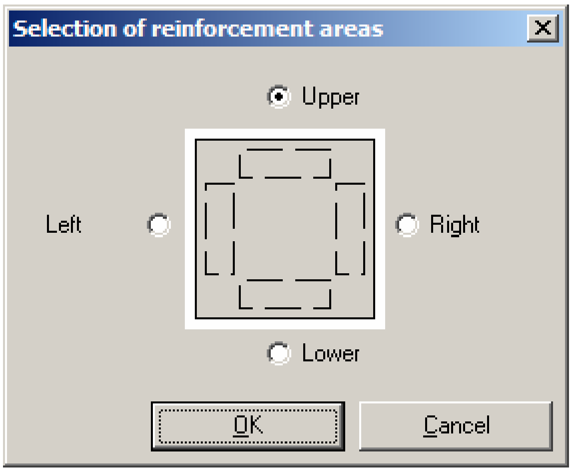
2.3 Rectangular section, reinforced concrete

To define reinforced concrete sections, different options are available to the user. Either you define a section within PowerFrame using one of the pre-defined section types, or you draw the section shape within Section Utility. In the first case only the gross cover must be defined, the reinforcement will automatically be generated assuming a constant distance between reinforcement steel and exterior concrete surfaces. In the second case the reinforcement areas must be drawn explicitly on the section shape. This procedure allows for an extremely broad range of possibilities (application of different steel grades and gross covers for different reinforcement areas, definition of reinforcement areas for sections with arbitrary shapes,...).

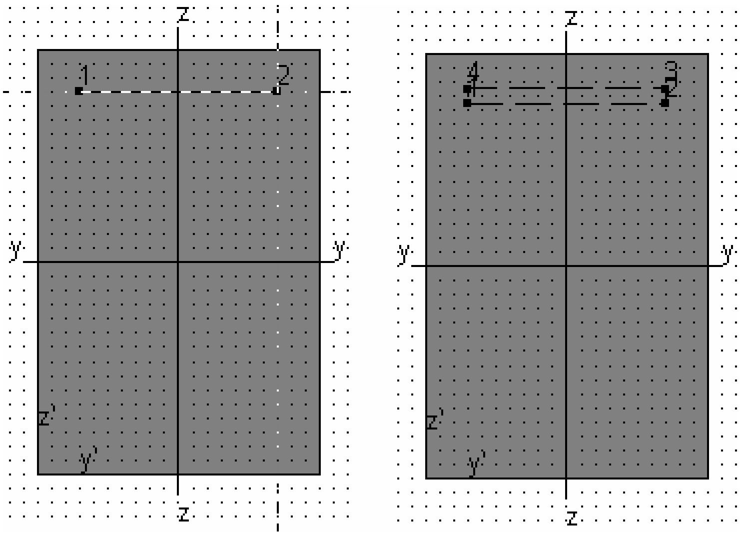
We decide to use the second option and therefore we define within Section Utility a rectangular section R30/40 with concrete grade C25/30.



Now use the  icon to define the reinforcement areas. In the dialogue window, select the upper reinforcement zone to define its position within the rectangular cross-section.



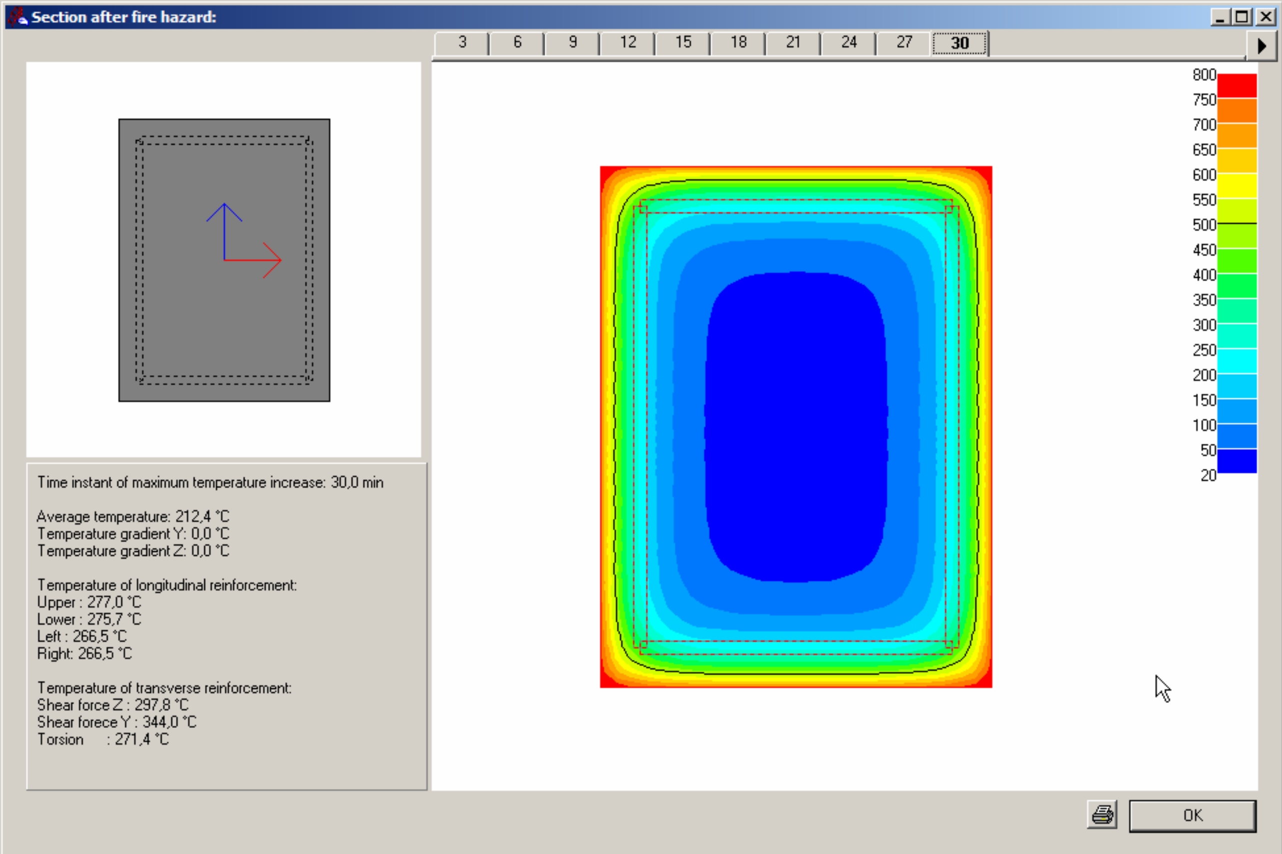
Then draw the center line of this reinforcement area at a distance of 30mm from the upper edge and click with the right-hand mouse button.



Repeat this operation to define the areas for the bottom and left/right reinforcement bars.

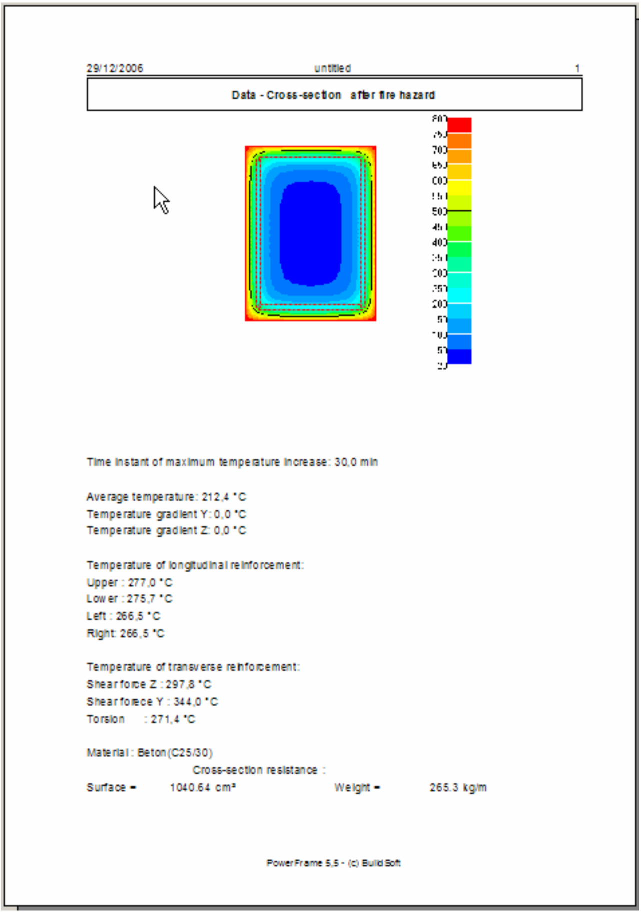
Remark: The definition of transverse reinforcement areas is required to enable the calculation of shear force reinforcement.

The elastic analysis is performed, and then we can double-click on the beam element in the 'Plot'-window to visualize the temperature distribution within the rectangular cross-section.



After 30 minutes, the average temperature of the section is 212.4℃. Given the section’s double symmetry and the fact that all exterior surfaces of the concrete beam are exposed to fire, no temperature gradients will develop under any circumstances.

The window also reports further information which is mandatory for a correct calculation of reinforcement quantities. Reduced yield strength of steel is derived from the average temperature of longitudinal and transverse reinforcement. The resistance characteristics of the reduced concrete section are summarized in the report than can be generated through the icon.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Data - Cross-section after fire hazard

Time instant of maximum temperature increase: 30,0 min

Average temperature: 212,4 °C
Temperature gradient Y: 0,0 °C
Temperature gradient Z: 0,0 °C

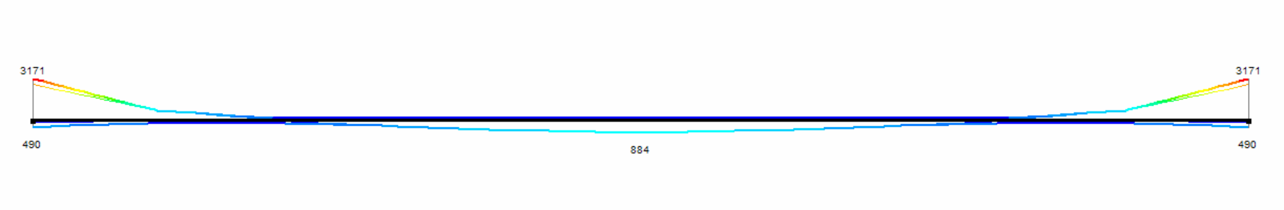
Temperature of longitudinal reinforcement:
Upper : 277,0 °C
Lower : 275,7 °C
Left : 266,5 °C
Right: 266,5 °C

Temperature of transverse reinforcement:
Shear force Z : 297,8 °C
Shear forece Y : 344,0 °C
Torsion : 271,4 °C

Material : Beton(C25/30)
Cross-section resistance :
Surface = 1040.64 cm² Weight = 265.3 kg/m

PowerFrame 5,5 - (c) BuildSoft

It should be noted that, in spite of the fire load which has been imposed, no extra longitudinal reinforcement is required as compared to an analysis at room temperature conditions.

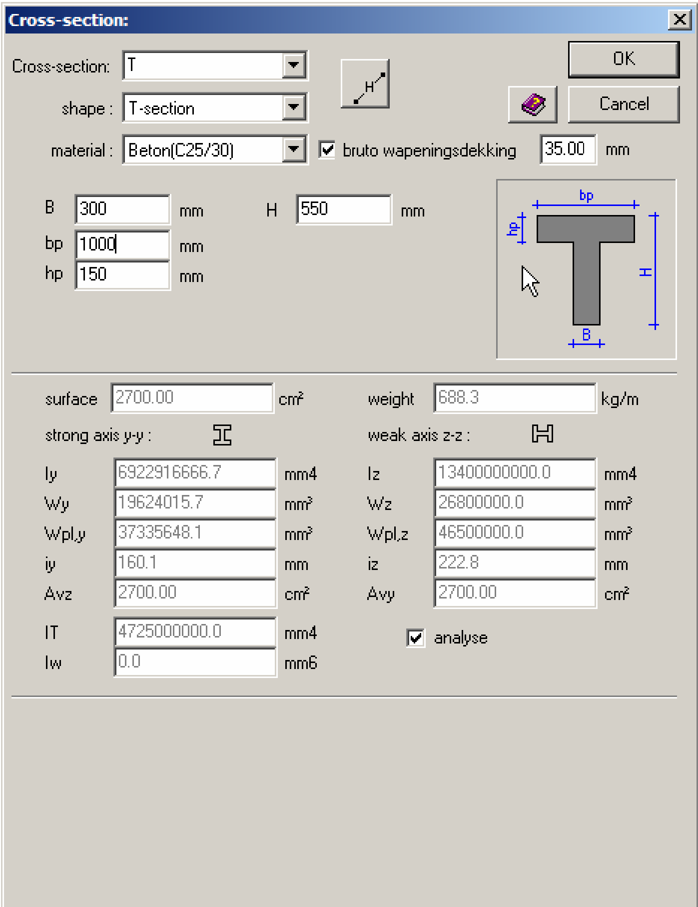


This can be explained by the following reasons:

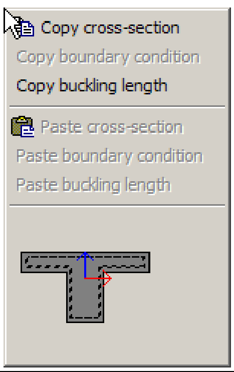
- the fire combinations ULS Fire represent a lower load compared to the fundamental loads combination ULS FC;
- the partial safety factors γ_c and γ_s for concrete & reinforcement steel are both taken equal to 1;
- the temperature increase of the section is quite limited, such that the yield strength of reinforcement steel is not really affected.

2.4 T-section – reinforced concrete

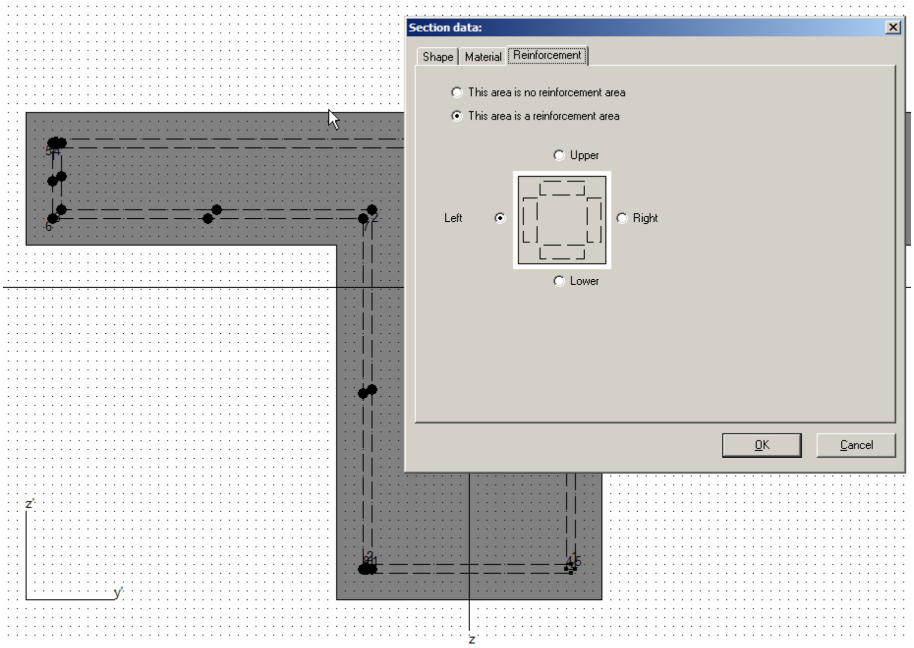
Let us now suppose that the R30/40 beam is cast on-site, along with the floor slab just on top of it. Consider a slab thickness of 150mm and an effective width for the corresponding equivalent beam of 1000mm. This way, we will define a T-section in PowerFrame with following dimensions:



Now select the beam element and click on the right-hand mouse button. A pop-up menu will appear, presenting an image of the cross-section that we just defined.



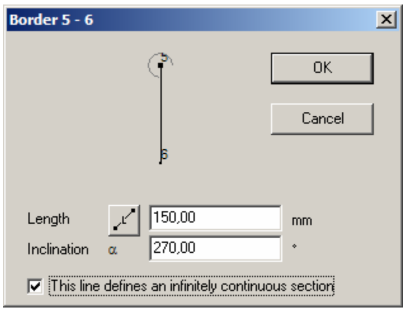
Click on this image to launch Section Utility. You will notice that the reinforcement areas are now recognized automatically. Double-click for example on the left transverse reinforcement area and activate the third tab page.

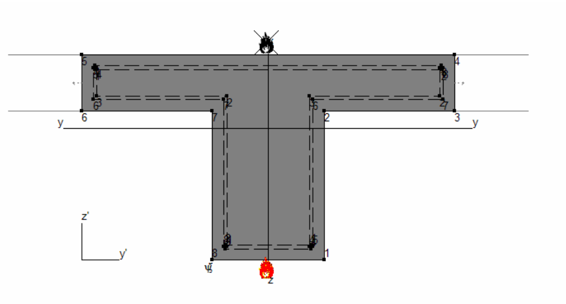


Remark: The transverse reinforcement sections are assumed to be uniformly distributed over the areas that have been defined. The calculated reinforcement quantities related to bending moments with respect to the section's weak axis will therefore depend on the position and the shape of the corresponding reinforcement area.

Furthermore, we want to impose that the beam and slab will only be exposed to a fire hazard at the bottom side. Therefore, we use following approach:

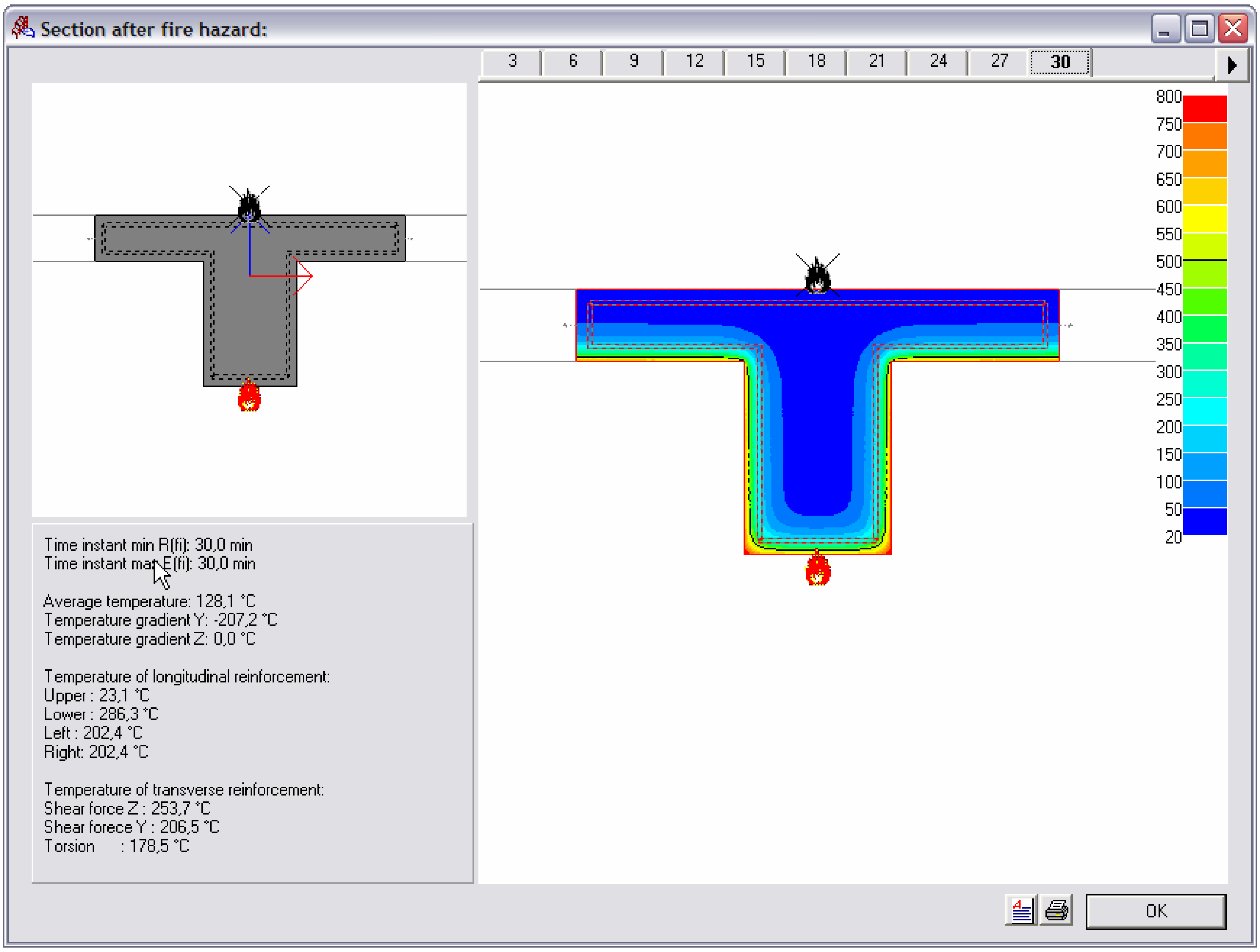
- Declare the section to be editable – instruction 'Edit – Make a library section editable'.
- Double-click on the slab edges at the left and the right to specify that edges actually define an infinitely continuous slab.





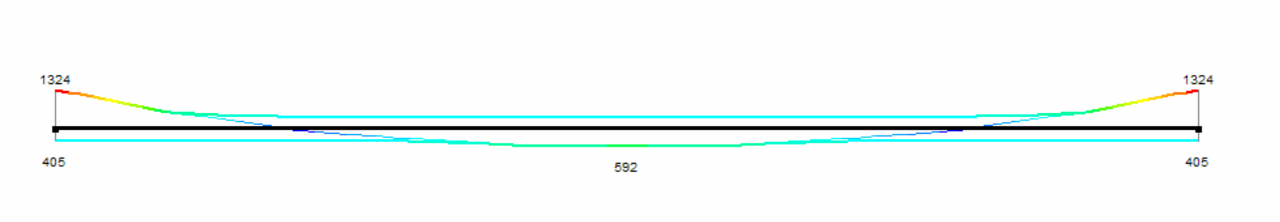
- As a result of this operation, Section Utility will identify two volumes that could potentially include a fire source. Those volumes are indicated by a red burning flame icon.
- Extinguish the upper flame by clicking on it with your mouse, to specify that no heat transfer is allowed from the upper volume to the floor slab. The colour of the flame will change from red to black.

Now that all properties of the section have been fully defined, the thermal & elastic analyses can be launched. This will deliver the following temperature distribution in the cross-section, at t = 30 minutes :



As a result of the section's non-symmetry with respect to the y-axis and because of the non-uniform temperate distribution within the cross-section, temperature gradients will develop with respect to the y-axis. As the standard design method is used however, those thermal loads will not be introduced into the global elastic analysis and will thus not give rise to any internal forces within the element.

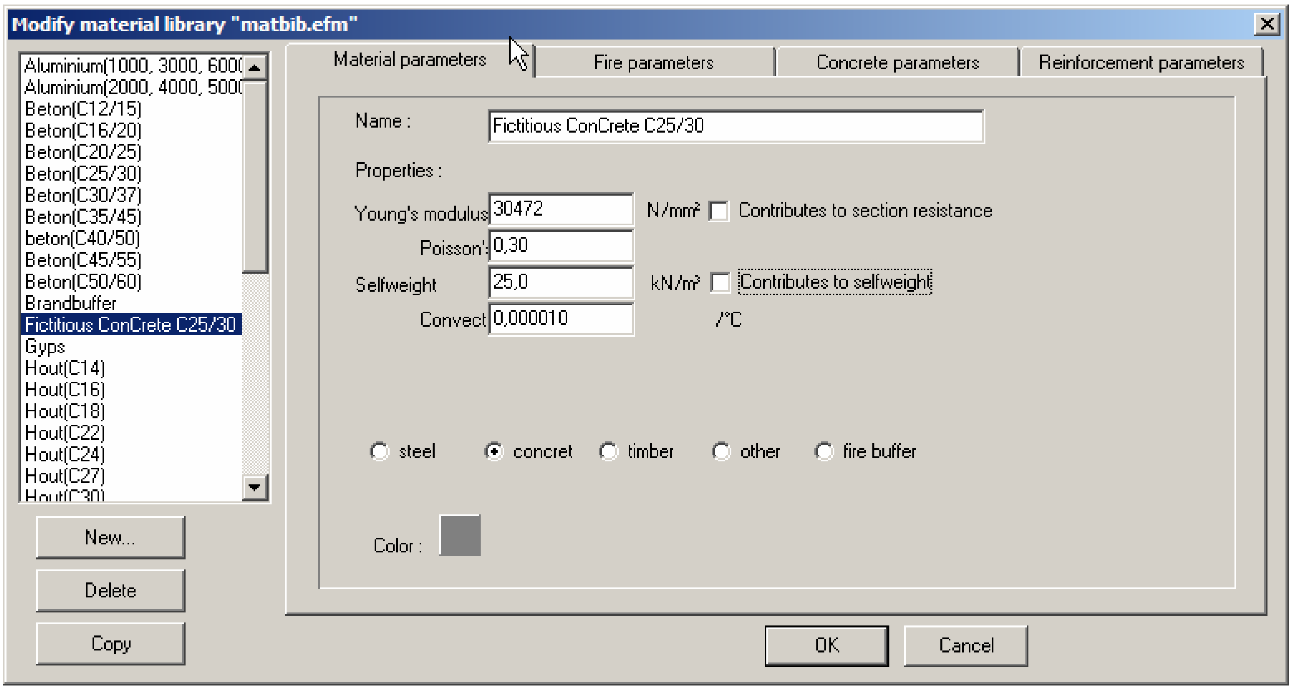
Also in this example, the combinations ULS FC, SLS QP and SLS RC will be more severe than the fire combination(s). As the floor slab plate is now a part of the resisting cross-section, lower reinforcement quantities will be delivered by the calculations.



2.5 Floor slab on rectangular concrete beam element

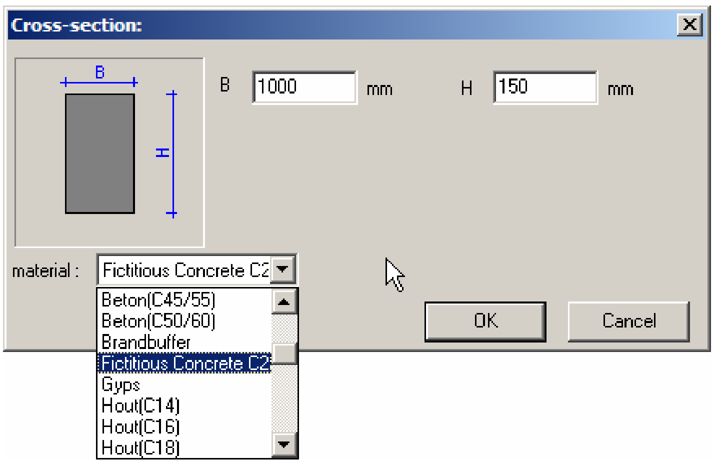
We now retake the previous example, but consider the slab to have no contribution to the R30/40 beam stiffness. It is furthermore assumed that the slab's self weight (3,75 kN/m) is accounted for in the permanent load case, such that only the thermal inertia of the slab will be introduced into the calculations. The fire hazard is supposed to act only at the bottom side of the slab.

Before you specify the cross-section, define a new material named 'Fictitious Concrete C25/30' for which you eliminate the selfweight and stiffness contribution. To do so, open the material library and copy the existing material 'Concrete (C25/30)'. Eliminate the Young's modulus and selfweight contribution by deselecting the appropriate lines. All other parameters are left unchanged:



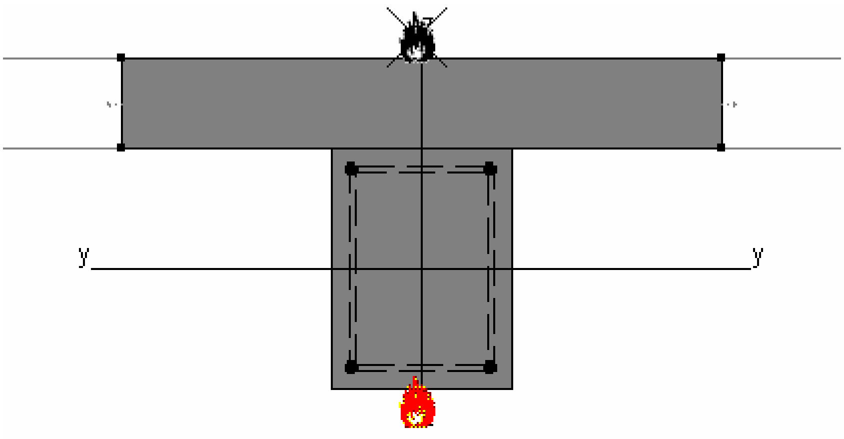
Now, the following steps can be taken:

- In PowerFrame, define a rectangular beam section of dimensions 300x400mm, gross concrete cover 35mm and material ‘Concrete (C25/30)’.
- In Section Utility, draw a slab element with a rectangular section of 1000x150mm by means of the  icon. Make sure to specify the correct material!

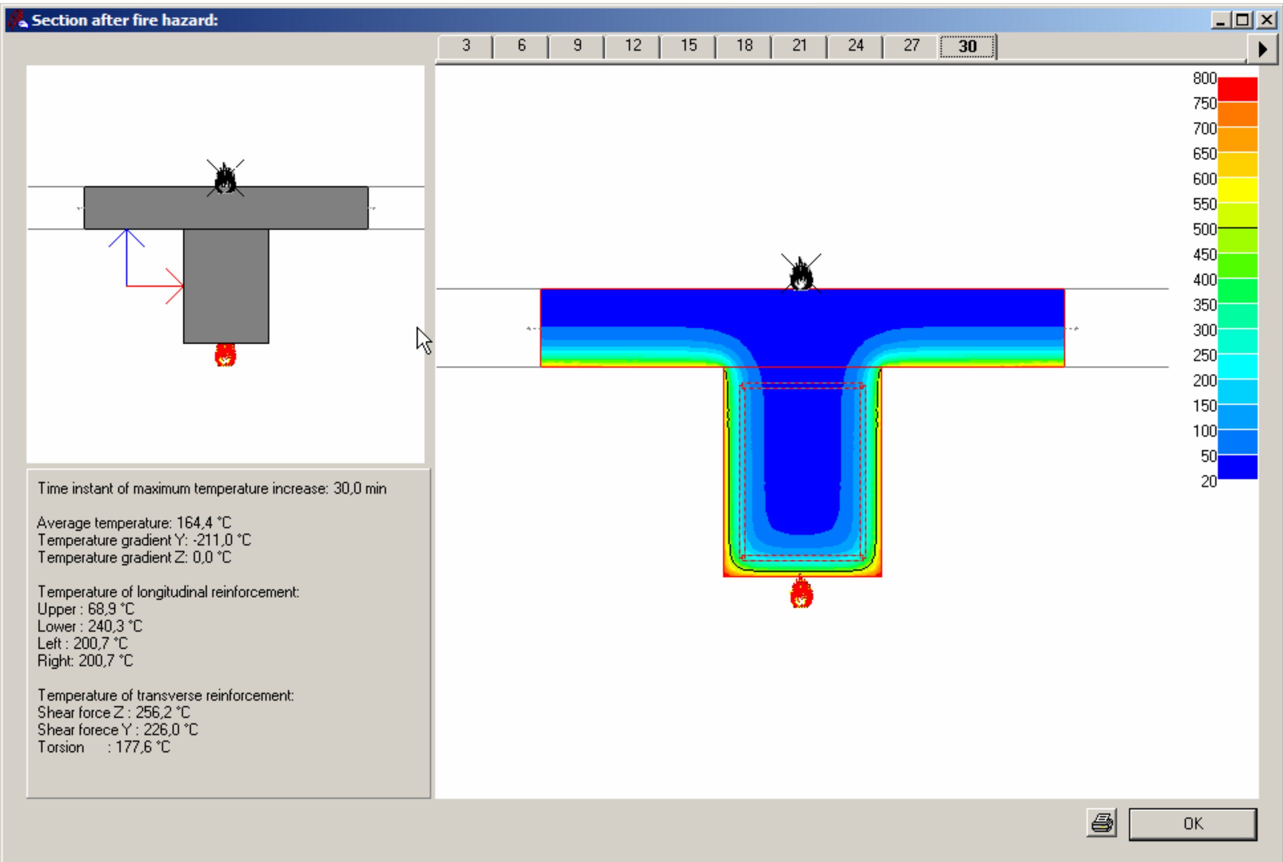


- Verify that resistance and selfweight properties have not been changed by adding the plate element to the section. Also make sure that the plate element is positioned correctly relative to the R30/40 section.

- Make the section editable, double-click on the plate edges at the left and the right, and specify that those edges define an infinitely continuous plate (refer to previous example).
- Now extinguish the upper flame using your right mouse button.



Take this section back to PowerFrame and launch the analysis. This will deliver the temperature distribution below at t = 30 minutes:



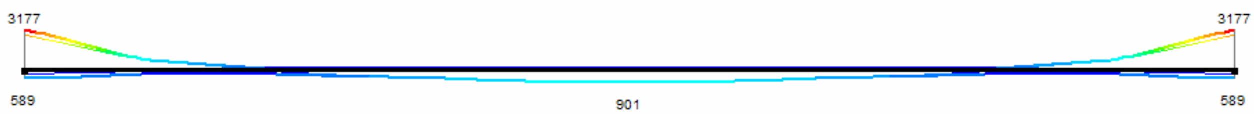
The following conclusions can be made:

- The temperature distribution does not depend on the strength characteristics of the materials. In other words, the temperature distribution above is identical to the one that we obtained in the previous example.

- The average temperature of the concrete beam has significantly increased. Indeed, the average temperature is evaluated for the part of the section which contributes to overall resistance (in this case, limited to the rectangular R30/40 section).

- Apart from the bottom reinforcement, all steel temperatures are now much higher. The reinforcement areas are now limited to the rib part of T-section, as the slab element does not have any contribution to section resistance.

Let us now calculate longitudinal reinforcement quantities.



Compared to the previous example, the top reinforcement has more than doubled. The rectangular section's moment of resistance is indeed considerably lower than for the composite T-section. Again, the ULS FC – SLS QP & SLS RC are more critical than the fire combination(s).