Problems in Simulating the Effects of a Fire on a Beam

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Summary

This paper is based on the experiences the author has gathered on a project performed for a civil engineering company. The goal of the project was to determine whether a special purpose steel beam surrounded by concrete as utilized in office buildings would be able to survive a fire lasting 60 minutes or not.

This paper deals with the problems related to load specification, getting the correct material specifications, and modeling issues.

Keywords

Fire, Thermal Loading, Material Properties, Modeling, Transient Thermal Analysis, Non-Linear Static Analysis, ISO 834

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Introduction

A fire, being rather unpredictable in its nature, is not something that is easily simulated with a deterministic tool like a Structural Finite Element program. However, if a Finite Element program is the only tool available, the user has two options. One option is to run parameter studies (i.e. very many simulations), the other is to run one simulation covering all possibilities. In both cases, several assumptions must be made.

In this particular case, the beam may be considered as built up of six layers, the layers being (from top to bottom):

Wood
Grout
Steel
Concrete
Steel
Grout

The first part of the work reported here was to determine the temperature distribution within the beam after the beam has been exposed to a fire during 60 [min]. A transient, non-linear thermal simulation was performed. It had to be a transient analysis to properly account for the material(s) being heated up, and it had to be a non-linear analysis since the thermal material properties are temperature dependent. At this point, it should be mentioned that a literature search did not find any report on similar simulations.

Subsequently, a (non-linear) static analysis was undertaken to address the question of collapse. The temperatures computed for a real time of 60 [min] were introduced to account for the temperature dependent material properties. It was not deemed necessary to account for path dependency due to time dependent temperatures.

Thermal Load Specification

First, assumptions concerning the fire itself had to be made. For this purpose, several norms and standards were consulted. To the analyst, the beauty of a standard is that it provides data that are of a "statistic nature but on deterministic form" (e.g. one value for heat transfer coefficients at all temperatures). It turned out that the standards in question basically would allow for two options for describing the fire, either

- temperature as a function of time (e.g. the ISO 834 curve); or
- heat flow per unit area as a function of time based on the amount and kind of material burning

The first alternative, the ISO 834 curve, was finally chosen. The other option seemed to yield even more unrealistic heat load than the ISO 834 curve. Neither case specifies a realistic time history of a fire, as the duration of the fire is specified as “indefinite”.
Also, it is doubtful whether the specification is realistic with respect to the maximum temperature developed. In short, it can be discussed whether the curves offered by the norms and standards are realistic or not.

The Thermal Loading was initially applied according to NS 3491-2:2003 /9/ as a heat flux, based on the ISO 834 temperature (curve) driving the flux. However, it turned out that the flux as given by /9/ would yield temperatures higher than the presumed driving temperature; hence the driving temperature was applied directly onto the surface of the structure in lieu of the flux.

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Material Properties

It came as a surprise that there is so little material data available at higher temperatures. Therefore, assumptions about the thermal and mechanical material properties at higher temperatures had to be made. In particular, it turned out – very unexpectedly – that steel properties at elevated temperatures are scarce. The steel used for the beam analyzed was a low carbon building steel, for which properties had to be guesstimated as several consulted sources failed to provide adequate information.

Many sources and publications were consulted. To be able to compare some of the data, four columns of data are given in the Table M1-1 below. The data displayed is the data that is *believed* to come from the "best" sources.

Certain data was taken from the norms. The parameter with the biggest influence on the temperatures for the simulations is the film coefficient. Here, the film coefficient between grout and hot air at the bottom of the beam was taken from the pertinent norm. Between wood and ambient air, the film coefficient had to be guesstimated. /6/ suggests a value of 3 – 20 [W/(m^2*K)]; this is a rather wide range.
The heat transfer coefficient between the wooden floor and the environment (i.e. air supposed to stay at 20 [˚ Celsius]) was arbitrarily chosen, since it has been assumed that it is of minor influence on the temperature distribution

It has proven impossible to obtain reliable data for the steel utilized in the beam. The steel utilized, DOMEX 640XP from SSAB Tunnplåt AB, is a low carbon steel composed of 0.12% C, 0.4% Si, 0.03% P (Max.), and 0.01% S (Max.) with additions of Al, Nb, V, and Ti. SEW 310 (/5/) has no data for this steel type, the closest might be 15MnNi6-3. MMPDS (/6/) is a very thorough source for material data, but basically list data utilized in the aircraft industry. Other sources were consulted as well, as an example shall MatWeb (http://www.matweb.com) be mentioned; it has no data for temperature dependent modulus of elasticity. It shall also be pointed out, that data points for temperature dependent properties typically end at 600 [8 Celsius]. Therefore, educated guesses had to be made concerning DOMEX 640XP as with all other materials utilized. An example hereto is given in Table M1-1 together with data from Reick (/4/), SEW 310 and MMPDS to demonstrate how widely data might vary.

Modeling Issues

Although the geometry and topology of the structure is fairly simple, an accurate thermal and structural simulations of the structure were deemed extremely difficult. One issue is finding valid material properties (in part discussed above), another is to correctly account for the behavior of concrete and its interaction with the surrounding steel.

The following issues should be considered when modeling the interaction steel – concrete:

- Material behavior
  - the concrete is capable of carrying a bigger load in compression than in tension without failing
  - the concrete will crack
  - the concrete may spall (and end up as "sand")
  - the concrete may crush (and end up as "sand")
- Contact behavior
  - initially, the interface steel – concrete will have shear carrying capabilities
  - after separation, the thermal behavior will change
  - after separation, not only normal compressive forces are transmitted, but also shear forces due to friction
  - when (if) the concrete has disintegrated, the sand may still act in shear and compression

The issues above are considered the more tricky ones. Also, it becomes obvious that a very careful stepping through the load history must be performed. Subsequent to the initial thermal simulation, several loadsteps must be monitored to catch any change in the structural configuration that might change its thermal properties. If any such change is found, the thermal simulation must be restarted from the point in time when the change occurs, and the process repeated until the ultimate true time to be simulated.

		Modulus of Elasticity for Steel in [GPa] as a Function of Temperature [8 Celsius]			
Temperature [8 Celsius]		Reich /4/	SEW 310 /5/ for 15MnNi 6-3	MMPDS /6/ for 4130 / 4340	DOMEX 640XP /7/ (educated guess)
0		213.0		213.0	
20.00			210.0	212.0	210.0
37.38					
93.33					
100.00		210.0		207.0	
148.89					
200.00		202.4		199.0	
204.44			199.5		
260.00					
300.00		183.2		192.0	
315.56			190.1		
371.11					
400.00		151.2		184.0	
426.67			174.3		
482.22					
500.00		110.8		175.0	129.8
537.78			147.0		
593.33					
600.00		63.9		164.0	113.1
648.89					
693.33					
700.00					
704.44					
748.89					
760.00					
800.00					
815.65					
848.89					
871.11					
900.00					63.0
1000.00					
1100.00					
1200.00					
Table M1-1		**Modulus of Elasticity of Steel as a Function of Temperature**			

Given the uncertainty about the thermal load and material properties, another approach was taken. Since the purpose of the simulation was to determine the likelihood of collapse, it was assumed that

1. There is perfect contact between steel and concrete at all temperatures
2. The thermal expansion coefficients of steel and concrete are the same
3. The modulus of elasticity of concrete is a fraction (say 1/10 or less) of that of steel at all temperatures

The implications of these assumptions are many. The main thought was to include the concrete to be able to introduce the structural loads and supports in a supposedly meaningful way, and also to be able to account for the stabilizing effect of the (partly cracked, crushed, and spalled) concrete. And, given that the concrete actually carries a bigger load than its reduced modulus of elasticity allows for, the assumptions are conservative.

The modeling itself was pretty straight forward. The simulations were run in ANSYS Rel. 7.1 and 8.0 /1/, /2/, /3/; no special "tricks or tweaks" were needed, only considerable computer time.

The results obtained seem reasonable, and reflect the fact that concrete is a very good thermally insulating material. Most of the assumptions made can not be verified. However, the essential outcome for the beam analyzed, is that it does not need the help of the concrete to avoid collapse.

Conclusions and Final Remark

More realistic thermal load specifications for a fire are needed. Possible approaches to obtain realistic data could be

- Experiments in controlled environments (expensive, many experiments needed)
- Numerical Simulations (special purpose software must be developed, calibration with measurements needed)
- Data gathering “on site” upon arrival of the fire brigade

The first two alternatives are self-explaining. Data gathering on site would require that the fire brigade is furnished with data gathering equipment that is placed out on arrival. It is anticipated that useful data could be collected in this way.

The available material data does not reflect the recent developments in simulation software. For extreme applications (e.g. calculating the effects of a fire on a steel structure), the company that first is able to offer complete data sets for their steels will most likely have a business advantage.

A final remark: An extensive search for similar simulations by the Finite Element Method on the World Wide Web did not result in any findings of interest to the author. He would welcome all references that could possibly be of interest.

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