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GLOBAL MODELLING OF STRUCTURES IN FIRE

Description

Most building structures are required by design codes to be able to resist fire. However, until recently the manner in which fire loading has been handled by codes has been different to the manner in which other loads such as gravity, wind and earthquake have been handled. Whereas it has been normal to ensure structures are able to resist these sorts of loads by means of rationally based calculations, fire resistance is conventionally assessed by reference to a test known as the Standard Fire Test. This test bears little relation to the kind of fires that are likely to occur in real structures and requires that the structural system tested bears very little resemblance to the behaviour of any but the simplest real structures. The shortcomings of the Standard Fire Test have been highlighted by many authors from both fire dynamics and structural engineering perspectives. Despite this, the test (or tabulated results of it) is still widely used for routine structural design. Increasingly, however, designers are recognising the lack of rationality that relying on the Standard Fire Test involves and also finding that the limited range of structures to which it may be applied restricts the opportunities for using economic and innovative structural fire safety designs

Some fire design codes have now introduced the possibility of designing structures to resist fire by calculation. In principle therefore it is now possible for designers to treat fire loading in the same manner as any other form of load. However, for this to happen it must be possible for designers to predict with confidence how a structure will respond to fire. Considerable research effort has been dedicated in recent years to providing the knowledge needed for this and much progress has been made. It turns out that structural behaviour in fire in all but the simplest cases is much more complex than analyses based solely on loss of material strength due to heating can predict. A key aspect of the findings is that treating structural elements, such as beams and columns, in isolation in a fire analysis is insufficient. For accurate results to be produced, either the behaviour of whole structures or the behaviour of parts of structures with appropriate boundary condition must be considered. As a result in all but the most straightforward cases numerical analyses are required to accurately predict the strength and behaviour of structures in fire.

The purpose of this datasheet is to distil the experience gained over the last decade or so of modelling fire affected structures so that new-comers to the field can rapidly appreciate the requirements, challenges and current limitations of global modelling of structures in fire.

Nature of Global Modelling of Structures

Analysing and designing structures for fire loading is a particularly challenging problem for structural engineers. To see that this is the case it is worthwhile contrasting the analysis processes for ambient and high-temperature structural design. At ambient temperature a fortuitous combination of facts regarding loading, material behaviour and design requirements mean that when analysing structures a number of greatly simplifying assumptions may be made. In fire conditions these assumptions no longer hold and both analysis and design become correspondingly harder.

At ambient temperature "actions" on a structure typically result from a combination of wind and gravity loading. Such actions are forces and are (or can reasonably be assumed to be) non-varying when estimating strength. As a result the stresses in structures can be regarded as constant for each load case and it is straightforward to design for sufficient strength. Simplifications may be made as a result of most commonly used structural materials being very stiff. This means that deflections can be considered to remain small and geometric non-linearity can generally be neglected in analyses. In most structures, small deflections are also ensured by serviceability requirements. It is also usually possible to assume either linear elastic or rigid-plastic material behaviour, further simplifying the analysis process by removing the difficulties of handling material non-linearity in calculations. This simplification is even possible with concrete, which is a non-linear material, by use of equivalent stress blocks.

The situation at elevated temperatures is very different for several reasons. The actions on a heated structure are primarily temperatures, or more fundamentally heat-fluxes, that result from exposure of the structure to hot gases and radiation. These produce heating and, subsequent to a fire or as a result of fire-fighting, cooling of the structure. Since not all parts of the structure heat at the same rate, and because structural elements expand when heated, stresses that are not present at ambient temperature are produced within the structure. Whereas the stresses in a structure at ambient temperature may be considered constant, this is not the case in a heated structure because thermal equilibrium will not occur during a typical fire. The inter-play between thermal expansion, restraint to this expansion and the large deflections commonly present in fire conditions, also result in stresses within structural members varying during a heating-cooling cycle. There is no reason why the largest stresses should occur simultaneously with the peak of either the applied heat fluxes or the structural temperatures. A further complication is that heating and cooling will not occur simultaneously in all parts of a structure. This means stresses may be increasing in some areas but decreasing in others.

High temperatures also affect structural materials' mechanical properties with key factors being loss of linearity, strength, modulus and a clear yield point. These changes mean that not only do the stresses within a heated structure change with time but so too does the structure's strength, and this must be considered during analyses. A second consequence of heating is thermal expansion. As noted, if this is restrained in any way, large stresses will result. Thermal expansion also frequently causes large deflections to be present in heated structures. As these deflections are caused by the changing length of heated members it is not necessarily the case, as at ambient temperatures, that they indicate impending failure. Indeed it may be the case that large deflections allow thermally induced stresses to be relieved. However, large deflections do mean it is necessary to account for the effects of geometric non-linearity in analyses if accurate results are to be produced.

The above discussion shows that to get an accurate prediction of structural behaviour at high temperature it is necessary to consider in analyses all the following factors that may typically be excluded or disregarded under ambient conditions: material non-linearity, geometric non-linearity, and time- and temperature-varying strength. If a structure is to be designed to resist fire it is necessary to ensure the structure has sufficient strength and fulfils other design requirements during the entire period it is exposed to temperatures above ambient. The complex and time varying nature of both stresses and strength in heated structures means it is not possible to identify a most serious set of applied temperatures in the same way as a most serious load case can be identified at ambient temperature. Fire loading is a very rare example in structural engineering where all these phenomena need to be considered simultaneously to predict behaviour. Blast and earthquake loading offer two somewhat comparable forms of loading but in these cases other simplifications, such as assuming a lumped mass, may be considered.

The complexity of the behaviour of heated structures has traditionally not been recognized in fire safety design calculations because assessing fire resistance has almost always been done with reference to the Standard Fire Test or has assumed that individual elements of structure may be considered in isolation from each other. In other words, structural fire design has tended to assume statical determinacy. In these conditions high temperature strength calculations only need to account for loss of material strength to obtain a reasonably accurate critical temperature. However almost all real structures contain a degree of redundancy and simplistic calculations will not provide accurate estimates of strength.

Technical information

SOFTWARE

The complexity of even the simplest structural-fire problems means that a numerical analysis will be needed. To date the finite-element method has been used almost exclusively and it seems likely that this will remain the only realistic choice in the foreseeable future. There are, however, choices to be made over the nature of the code to be used. Finite element codes suitable for structural-fire analyses can be broadly divided into two categories: commercial general purpose codes such as Abaqus, Ansys, Oasys, LS-Dyna etc; and research-based codes such as Vulcan, Adaptic and Safir. Commercial codes have the advantages of being able to handle larger problems than research codes and having a wider range of capabilities outside fire engineering. This means that if a structure needs to be analysed for several loading conditions, perhaps fire and seismic loading, only one model would be needed. Commercial programs are, however, costly and normally restrict the ability of the analyst to extend or alter the code. This "black-box" aspect can be frustrating if numerical convergence is not achieved but the reasons for this non-convergence can not be fully investigated. By contrast research codes tend to be much cheaper and the analyst may have access to the code and thus be able to adapt it according to need.

TYPES OF ANALYSIS

There are several decisions to be taken regarding the type of analysis to be undertaken. Depending on the situation any of the following may be required

- An analysis where the mechanical loading is held constant while the thermal loading varies. This represents most fire scenarios reasonably accurately and is the most common form of analysis. Typically the analysis would be broken into two load steps, the first being the mechanical loading and the second the temperature loading.

- An analysis with increasing mechanical loading while the thermal loading is held constant. Such an analysis could be used to find the ultimate mechanical loading for a specific temperature.
- Both mechanical and thermal conditions are time dependent. While probably strictly the case for most structural-fire problems, such analyses have rarely been performed and for most buildings structures this level of detail does not seem to be required. Obtaining accurate estimates of the variation of mechanical loading as a fire developed would be difficult.

There are also various means by which the temperature loading can be represented

- The temperature within the structure can be specified and then a purely mechanical analysis performed. This requires that the temperatures are available either from estimates (perhaps based on simple heat-transfer calculations) or test data.
- The temperature within the structure is calculated based on a finite-element heat-transfer calculation conducted separately to the mechanical analysis. This requires knowledge or an estimate of either the surface temperature of the structure through time or the net heat-flux at the surface of the structure through time.
- A fully-coupled thermal-mechanical analysis. In general this is not required for structural-fire problems as there is normally only weak coupling between heating and stresses/strains. However, there may be special circumstance when it would be needed. One advantage of this approach is that only one analysis is required and so no data transfer from a heat-transfer analysis to a stress analysis need be undertaken.

The most appropriate numerical scheme used for a given analysis must also be selected.

- A quasi-static stress analysis. Here time is a non-physical solution parameter and no time dependent phenomena, such as inertia forces, can be represented. Since inertia effects are not modelled, such an analysis is only appropriate for predicting structural behaviour where structural movement is slow; quasi-static analyses are not suitable for collapse modelling where large inertia forces will be developed. Convergence problems may arise from local buckling instabilities within a large structure with this kind of analysis. Softening and buckling behaviour at ambient temperature is sometimes handled in quasi-static analyses by using an "arc-length" algorithm to solve for load and displacement simultaneously. For analyses with varying temperatures the use of arc-length methods is generally not possible because the applied loads on a structure remain constant.
- A dynamic stress analysis. Here time has physical meaning and so inertia forces can be captured. Dynamic explicit analyses use a conditionally stable numerical scheme which can require small time-steps and so can take a long time to reach a solution. Mass-scaling may be required to obtain a solution in a reasonable time. Full-collapse behaviour can be modelled with this kind of analysis. Since dynamic explicit numerical models will generally reach a solution of some kind (even if it is not a physically meaningful one) without the convergence problems associated with quasi-static analyses, it is recommended that very careful benchmarking is undertaken of such models. This process may include running a quasi-static analysis until inertia forces become significant and comparing the results with the dynamic analysis predictions up to this point.

MATERIALS

Steel

The behaviour of steel at high temperatures is fairly well understood and the usual models used at ambient temperature (von-Mises plasticity with hardening) are still applicable at elevated temperatures. Details of the hardening curves for structural steel are given in a number of publications, notably Eurocode 3. Stresses resulting from thermal expansion are often of great importance in heated structures so the correct coefficient of thermal expansion (which is temperature dependant) should be included in numerical models. This quantity is also included in the Eurocode 3, as are the thermal properties that are needed for heat-transfer analyses.

Concrete

Concrete is a much more complex and variable material than steel, and even at ambient temperatures numerical modelling of concrete structures is less accurate than modelling of steel structures. It is important, therefore, that the limitations of any model used for modelling high-temperature concrete structures are recognized.
There are a range of constitutive models available for representing multi-axial stresses in concrete, most of which are based on some variant of a Drucker-Prager yield criterion. These can be used with uni-axial stress-strain-temperature behaviour from Eurocodes 2 or 4 to provide the means to model behaviour of heated concrete in a basic manner. The Eurocodes also provide information on the quantities such as thermal expansion and thermal properties of concrete. It should be noted that these are dependent on the type of aggregate used.

Many numerical codes allow for a range of phenomena that occur in reinforced concrete to be added to the basic constitutive model, such as cracking, tension softening, load-induced thermal strain, and damaged plasticity. While representing such effects at high temperatures is desirable, it is often not possible to determine suitable input parameters due to lack of experimental evidence. Cracking is the most commonly included phenomenon; it is usual to use a "smeared cracking" approach to representing the cracking behaviour of concrete. This approach assumes cracks are "smeared" over a finite length of concrete and so will not capture the large, discrete cracks that may occur in heated concrete structures. It is an approach that has been shown to be fairly accurate for modelling heated steel-concrete composite structures but its accuracy for other forms of construction that use concrete is currently not clear. Tension softening refers to the behaviour of reinforced concrete in tension after cracking has occurred. It is a complex phenomenon that depends on the interaction between plain concrete and reinforcement. In general it is difficult to capture accurately in numerical models and attempts to do so can lead to numerical instabilities.

Further developments

Research into global modelling of heated structures is continuing. The following is a brief list of areas where research may lead to greater capabilities in the near future, and areas which current modelling techniques are unable to handle.

- Modelling of local effects are often not currently included in models. There is a need to model connections, shear stud behaviour, effect of web openings etc without increasing the size of numerical models to point where they can not be run in a reasonable timeframe.

- There is considerable work being undertaken at present on improving the representation of concrete behaviour in numerical models. Much of this is focusing on how the important aspects of material behaviour that can not be easily included in current models are best represented. Of particular note are attempts to include load induced thermal strain (LITS) in models.
- The behaviour of structures cooling after a fire, or subject to localized or travelling fires, can be important and is increasingly being considered by researchers and analysts.

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Examples of Global Modelling of Structures

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