FIRE DESIGN OF CONCRETE STRUCTURES BASED ON A LEVELS-OF-APPROXIMATION APPROACH

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Abstract

Concrete structures, contrary to steel or timber structures, have not been traditionally considered as significantly sensitive to fire conditions. As a consequence, their performance in fire conditions has generally been assessed on the basis of quite simplified rules provided in codes of practice, mostly dealing with minimum geometric requirements in terms of thickness and concrete cover. Accidents under fire conditions have nevertheless revealed a certain level of vulnerability of concrete structures in fire and have thus shown that code regulations are potentially insufficient to cover this aspect of design.

As a reaction to this level of simplicity, some codes are currently available with specific and very detailed provisions with reference to fire design in concrete structures, such as EN 1992-1-2, covering a wide number of simplified and advanced design procedures. Unfortunately, the hierarchy of these procedures and which one is most suitable for a given situation is sometimes unclear for designers. In addition, it is probably not necessary to perform rather complex and detailed analyses for all types of structures, but the level of refinement can be adapted to the sensitivity of the structure to fire conditions and to its significance for the society.

In this paper, a possible approach for consistent design of concrete structures under fire conditions is proposed based on the Levels-of-Approximation philosophy. The Levels-of-Approximation approach has been successfully introduced into the new Model Code 2010 for a number of problems (such as shear, punching and 2nd order effects) and allows refining the accuracy of the analysis when necessary. This allows keeping simple rules for most cases but provides a general frame for assessing complex or sensitive structures. In addition, it does not only incorporate calculation methods, but specifies which ductility requirements are to be fulfilled in order to ensure a correct applicability of each method.

Keywords: concrete structures, fire design, Levels-of-Approximation approach, robustness, codes of design

1 Introduction

Concrete structures have traditionally been considered as structures with low sensitivity in case of fire. This is opposite to timber or steel structures. For the former, timber provides good insulation properties but is combustible (timber members are thus protected by external layers or over-sized). For the latter, steel is incombustible, but is an excellent heat conductor and its material properties are highly sensitive to high temperature. Furthermore, for steel members, not only the decay of material properties is significant, but also the overall structural behaviour, as steel construction is usually governed by stability criteria; therefore, steel members are potentially sensitive to the imposed displacements associated to fire conditions. As a consequence, and taking into account that concrete is neither combustible nor significantly sensitive to stability issues, the treatment of fire conditions for concrete structures has been traditionally incorporated in design regulations in a quite simplified manner, mostly by providing minimum thicknesses and/or cover of concrete members. However, although concrete structures have shown lower sensitivity under fire conditions in comparison to timber and steel structures, collapses in concrete structures have also happened and have been reported. Some of them are reviewed below to address the vulnerabilities of concrete structures:

- Failure in columns by shearing under excessive lateral drift (Fig. 1a, b). This is probably one of the most known and reported issue for failures of concrete structures under fire conditions (refer for instance to the warehouse in Ghent reported in *fib* 2007). Failures are triggered due to an excessive drift of a column after heating of the top slab. Buildings with long distances between expansion joints and with limited deformation capacity of the columns (associated to low amounts of transverse reinforcement or to very large compression forces) are the most sensitive. It is worth observing that, whereas the aforementioned indirect actions (compression in the beams that turns into shear in the columns) are usually detrimental for the columns (unless specific detailing rules are adopted, as it is the case in earthquake-resistant columns), the effects of a compression force on the beams is generally beneficial (Vecchio & Collins, 1988).
- Failure in columns by second order effects. Similar to steel columns, also stocky concrete columns are sensitive to fire conditions (Kodur & McGrath, 2003), because of the fire-induced reduction of the section with the ensuing increase in slenderness. Currently, design of precast slender concrete columns based on technical approvals usually incorporate fire duration as a parameter for determining the minimum required dimensions.
- Punching in flat slabs with limited deformation capacity. Failures in punching have been reported under fire conditions in flat slabs (Gretzenbach car parking, Switzerland (Muttoni et al. 2008), Fig 2c). Evaluation of these cases and of punching behaviour under fire conditions (Bamonte, Fernández Ruiz & Muttoni, 2012) have shown that such failures are potentially governing for slab-column connections with limited deformation capacity mostly because of the increase of the reaction in the columns near the fire source (as a consequence of the redundancy of the system and of a non-uniform distribution of the heating sources, Figs 2a,b). On the contrary, severe fire conditions in flat slabs with sufficient deformation capacity (for instance shear-reinforced slabs as the accident of Jonen, Switzerland reported in (Muttoni et al. 2008), Fig 2d) have led to spalling failures of the outermost layers of concrete but without leading to a total collapse of the structure
- Loss of double curvature in shell members. Such elements have been reported as particularly sensitive to fire conditions. A case is shown in Fig 3b where double curvature thin shells collapsed during a fire in Bologna. Failures of shell structures are not associated to degradation of the strength of the material, but to the loss of double curvature conditions under the imposed strains originated by heating of one face (Fig 3a). The shells thus do not longer behave as membranes, but have to carry bending moments and shear forces and the available dimensions and reinforcement (designed for membrane behaviour) are insufficient to ensure the load-carrying capacity.

It can be noted from the above-reported cases that failures under fire conditions of concrete structures are mostly related to structural behaviour of members with brittle behaviour (increase of curvatures or redundant forces) more than to material degradation. This aspect seems somewhat contradictory to the traditional approach of codes providing minimum thicknesses of structural members but providing no rules on deformation capacity or structural requirements. Moreover, one key aspect of fire conditions are surely the large displacements triggered by the thermal dilation: this is in contrast with the usual assumptions concerning civil structures (specifically concrete structures), where displacements are very small, and equilibrium conditions are not affected by the deformation of the structural members.

A well-known reference to draw general considerations on the aforementioned failures under fire conditions is Eurocode 2, part 1-2 (2005, EN 1992-1-2), which represents probably the most advanced and state-of-the-art code for fire design at present time. This code (comprising 97 pages) incorporates a number of calculation methods to assess the structural resistance of concrete structures in fire. These methods present different degrees of complexity: tabulated data, simplified analysis methods (500 °C isotherm analysis and zone method) and advanced analysis methods (guidelines for performing detailed analysis). Although no explicit rules are given on which method is to be used or is most suitable for a given case, good engineering sense indicates to use first the simplest methods and to increase progressively thereafter the complexity (and accuracy) of the analyses. Applied in this manner, the EN 1992-1-2 has certain similarities to the philosophy of the Levels-of-Approximation (LoA) approach (Muttoni & Fernández Ruiz 2012a,b) which has been incorporated in Model Code 2010 (*fib* 2012a,b) for a number of topics such as design for shear and punching and 2nd order effects. This latter LoA approach proposes to use simple (and safe) design methods for preliminary or tender design and to increase the level of complexity (only for the members requiring it) for further stages of design (Fig. 4). The application of each LoA requires however to satisfy some conditions, typically on the deformation capacity or ductility requirements to ensure safe application of the calculation methods and hypotheses of the LoA.

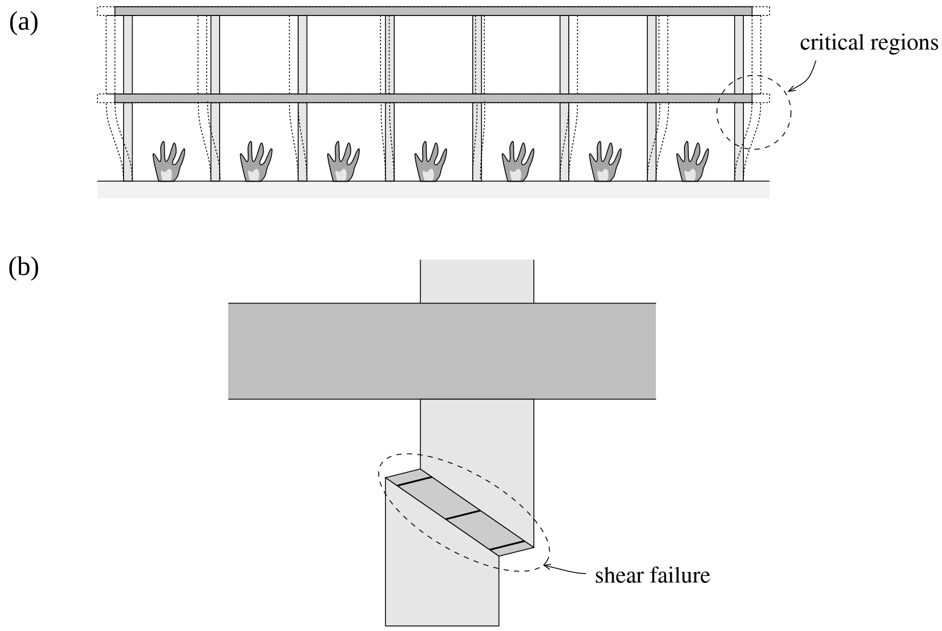

Fig. 1 Failures in columns: (a) excessive drift effect under fire conditions and (b) shearing of a column

Despite the similarities, one can see by comparing the LoA approach to EN 1992-1-2 that in EN 1992-1-2, although various design methods are available, the hierarchy between them is sometimes unclear, particularly when alternative design procedures are proposed, as well as the conditions to be respected for application of each method (such as the required ductility conditions, where only some general considerations are provided in EN 1992-1-2 for the advanced methods).

In this paper, an alternative approach to the previous ones (traditional simplified approaches and EN 1992-1-2) is proposed within a consistent strategy for robust fire design. It consists on implementing the design methods for fire following a LoA strategy and where the required conditions dealing with structural behaviour and deformation capacity to ensure safe application of the methods are provided. This allows ensuring simple and safe (ductile and robust) designs for preliminary design purposes and to increase the accuracy when required by devoting some additional time to the analysis (these analyses being thus less restrictive in terms of deformation conditions).

2 Governing aspects for robust fire design

On the basis of a number of well-documented failures under fire conditions, of the following potential failure modes can be identified:

- Degradation of material properties of a cross-section under high temperatures leading to a reduction of the strength/bearing capacity such that the member fails in bending, shear or punching
- Increase of 2nd order effects leading to buckling of members subjected to significant compression forces (Fig. 1c)

- Structural effects due to thermal expansion leading to excessive imposed displacements (Fig. 1) or to excessive statically redundant forces (Fig. 2a-c) in systems with limited deformation capacity (brittle behaviour)
- Spalling of the concrete cover. Such phenomenon may lead to local failures (at the spalled region, Fig. 2d) or may reduce the strength of the member such that it fails completely after cover spalling (global failure).

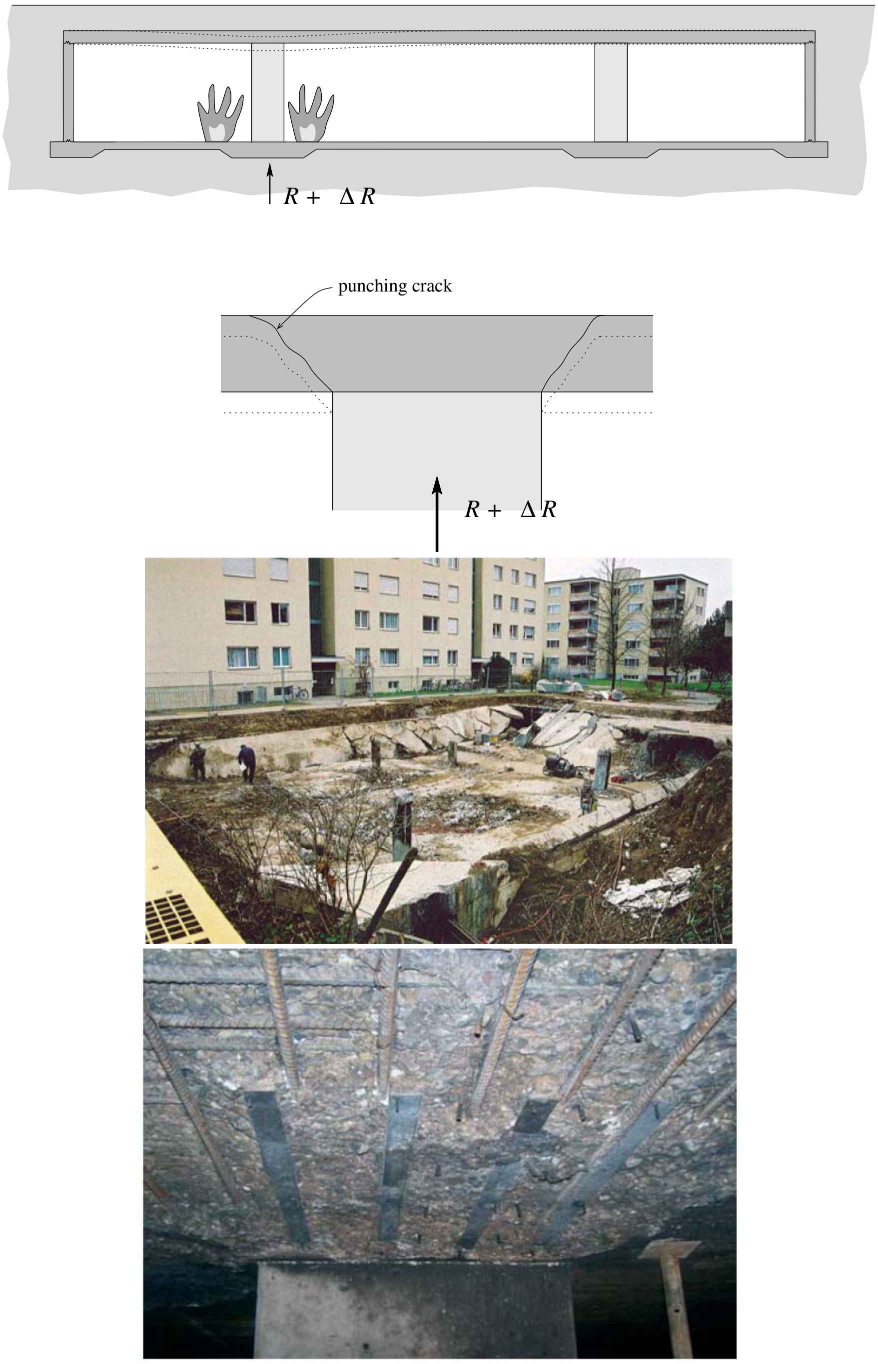

Fig. 2 Punching failures in flat slabs subjected to fire (photos courtesy of prof. A. Muttoni): (a) increase of the reaction force due to redundant forces; (b) development of punching crack; (c) Gretzenbach flat slab collapse; and (d) Jonen flat slab spalling

As it can be noted, failures are related to the material level (degradation of mechanical properties), to the element level (2nd order effects, local spalling) or to the structural level (effects of imposed strains and displacements). Robust fire design has thus to account for the influence of all of them:

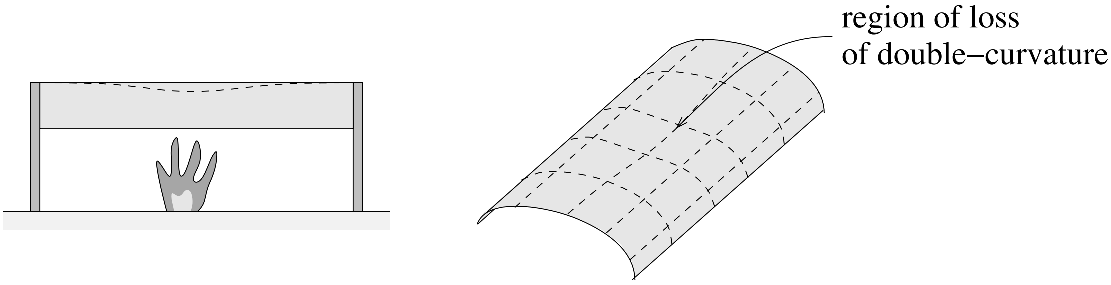

Fig. 3 Loss of double curvature in shell members: fire curvatures reducing double-curvature in concrete shells

- With respect to the material and sectional level, the influence of fire on the degradation of the mechanical properties of the materials can be minimized by providing sufficient concrete cover to delay the increase of temperature within the concrete section. This has traditionally been recognized as an efficient manner to protect concrete members against fire action and is in fact the most important parameter acknowledged concerning fire design in some codes of practice (*fib* 2007,2008).
- With respect to the element level, fire actions can be neglected for members that are little sensitive to imposed strains (associated to ductile failure modes) and where spalling is avoided. The latter phenomenon is complex (development of pore pressure upon drying of external layers of concrete) and dependent on several parameters (*fib* 2007,2008), where particularly the moisture content of concrete, the concrete strength and the acting compressive stresses are acknowledged to be governing.
- With respect to the structural level, thermal gradients have been reported as potentially overloading columns triggering punching failures (Muttoni et al. 2008) in slabs with limited deformation capacity. Also, for structures with large distances between joints, the imposed displacements may exceed the available deformation capacity of concrete frames or columns. Again, a sufficient deformation capacity is thus required (unless a large number of joints is introduced in the building).

3 Fire design based on a Levels-of-Approximation approach

When designing under fire conditions, the previous potential failure modes have to be avoided. Consistent rules for so doing can be simplified as tabulated data (yet providing typically a quite comfortable level of safety) or be implemented into numerical models providing refined analyses (most accurate approaches, but rather demanding in terms of calculation efforts). It is clear that simplified rules may be appropriate for design of a large number of structures (particularly conventional ones) and that advanced methods should be used only for unusual or sensitive structures.

Due to the fact that the different levels of analysis should be based on the same set of physical models, fire design on the basis of the previous concepts can be put in a consistent manner by using the Levels-of-Approximation (LoA) approach (Fig. 4). This allows incorporating the necessary requirements for satisfactory fire behaviour at sectional, element and structural levels. In the following a proposal of the authors for so doing is presented (a similar reasoning can also be applied to determining the fire action, from simpler analyses to more refined ones).

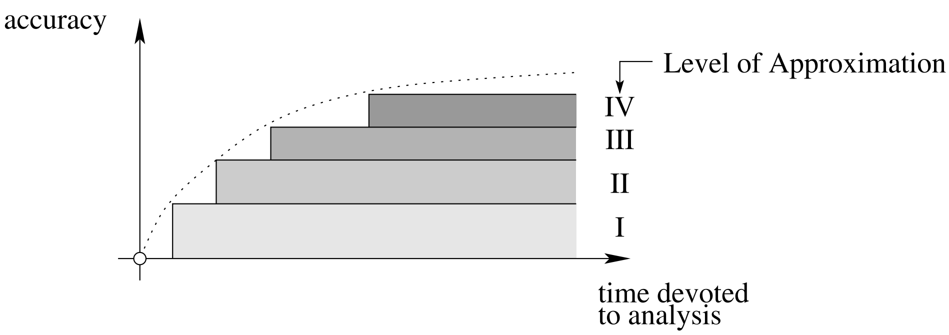

Fig. 4 Levels-of-approximation approach: accuracy of the estimate as a function of the time devoted to analyses

3.1 Level-of-Approximation I

This LoA is intended for design of most conventional structures:

- Requirements at sectional level:
  - Provide sufficient concrete cover and member thickness to avoid premature failure (tabulated data).

- Requirements at element and structural level:
  - Avoid brittle failure modes by incorporating transverse reinforcement in elements where shear and punching shear failures are potentially governing under imposed strains (statically-redundant structures).
  - Limit the slenderness of columns exposed to fire conditions (i.e. those inside the building) to acceptable values.
  - Limit moisture content of concrete below a given threshold. According to *fib* (2007, 2008), a reasonable value, quite independent of other acting parameter can be fixed around 3%. Such values of moisture content can in practice be obtained by ensuring exposition classes equivalent to that of concrete inside buildings with low air humidity. Alternative measures include the addition of polypropylene fibres (Liu et al. 2008), the addition of skin reinforcement or of protective layers

3.1 Level-of-Approximation II

This LoA is intended for peculiar structures not complying with the requirements of LoA I, particularly for the assessment of existing structures:

- Requirements at sectional level:
  - Detailed analysis on the basis of the isotherm method can be performed. This allows accounting for thermal profiles inside the concrete where the mechanical properties are updated on the basis of the concrete and steel behaviour. A detailed description of this approach can be found elsewhere (*fib* 2007, 2008, EN 1992-1-2). In general, it can be noted that tabulated data are obtained on the basis of this approach and that refinements are obtained when the isotherm curves are tailored to a specific situation or for updated material properties depending on temperature conditions. Two general remarks can be made on the use of the isotherm method:
    - the threshold value that is generally used to identify the reduced section (500°C) works well for ordinary concretes, i.e. concretes whose decay is well represented, for example, by the decay curves provided in EN 1992-1-2, or in simple problems (beams in pure bending, where the role of concrete in compression is of minor importance, or stocky columns, where the member behaviour is governed by the sectional behaviour); nevertheless, different values of the limit isotherm may be used, when concretes exhibiting a markedly different decay are used;

- the isotherm method is handy and easy to use, but is mainly conceived for hand calculations, since the estimation of the reduced section on the basis of the isotherm is something that is easily done from a graphical point of view; on the contrary, when the typical output of a FE thermal analysis (i.e. temperatures at the nodes or in the centroid of the elements) is used as basis for numerical calculations, the zone method is easier to implement. The zone method is also preferable, whenever concrete decay is markedly different from that provided in EN 1992-1-2. It is worth noting, however, that the applicability of the zone method (in the formulation contained in EN 1992-1-2) is limited to the exposure to the standard temperature-time curve.

- Requirements at element and structural level:
  - Analysis of statically-redundant forces and check of the bearing capacity under fire conditions for members exhibiting brittle failure modes;
  - In cases where spalling of the concrete cover is governing, the residual bearing capacity after cover spalling can be calculated by assuming full spalling of the concrete cover (from the exposed surface to the first layer of rebars) and accounting for statically–redundant forces due to imposed strains and displacements; in the case of columns, the strength after spalling becomes critical (main longitudinal reinforcement directly exposed to fire). For slabs, local spalling is potentially less critical, particularly provided that it develops locally and in regions away from supported areas (where punching may be governing Bamonte, Fernández Ruiz & Muttoni 2012).

3.3 Level-of-Approximation III

This LoA is intended for design or for assessment of structures that are particularly sensitive to fire or when a failure under a fire can lead to unreasonable consequences (nuclear plants, vital infrastructures). In this LoA, the general equations for thermal behaviour of concrete, moisture diffusion and mechanical behaviour of concrete and steel are coupled and solved into a numerical analysis. It is worth noting that the aforementioned coupling is generally a sequential coupling, i.e. the thermal analysis influences the mechanical analysis, but not vice versa, since the boundary conditions and the heat transfer inside concrete members is generally not affected by the displacements (although large), and the stress distribution (together with the presence of more or less diffused cracking).

Prior to the development of such models (time-consuming and with complex post-processing of data), the designer is encouraged to solve cases available in the scientific literature to confirm the suitability of the numerical methods used (benchmark cases). At this LoA, specific testing of some properties (such as spalling) and sensitivity analyses are also encouraged (type of aggregate and concrete, moisture content…).

4 Design requirements and architectural implications

Concrete structures represent an excellent alternative for constructions in which steel or timber are not suitable to ensure the required levels of safety in fire conditions without additional (sometimes sophisticated and difficult to integrate within the architecture) protective methods:

- medium and high rise buildings that require longer times for the evacuation of the occupants;
- parking lots with several stories, specially underground ones;
- warehouses with valuable combustible materials.

In all these cases, the absence of additional protective measures represents for a simplification of the construction process and a significant economic advantage towards concrete structures. This holds true not only for the initial investment but also for the maintenance that normally requires significant auxiliary equipment. Concrete structures are in this sense more robust and suitable, since their resistance is ensured by the base material and the durability of the fire protection does not require special treatments or the replacement of the protection material.

For design or assessment of concrete structures, the LoA approach can be seen as a suitable strategy for design. In this regard, it must be accounted that the widespread use of concrete structures in all kind of buildings and technological environments is related not only to its moderate cost and moderate labour skills required for their construction, but also to the easiness of the design methods that are required for most of them. Therefore, a simplified but consistent method that ensures a satisfactory level of fire resistance is essential to maintain the competitiveness of concrete structures in this field. In addition, suitably designed concrete structures do not need to be covered, hidden or protected and take an active part in the global architectural design perceived by the user.

With respect to the application of the LoA, it must be noticed that simplified design methods are suitable for most conventional structures. However, slender members (as concrete shells (Muttoni, Lurati & Fernández Ruiz, 2013) or slender prefabricated elements) would not satisfy simplified fire resistance conditions (such as minimum thickness) and could not be designed for or used in new constructions. Advanced design methods allowing for the use of such structures is thus a significant advance.

With respect to assessing the bearing capacity of existing concrete structures, the LoA is a particularly suitable approach as it allows refining the estimate of the strength, if necessary. Thus, simple checks can be performed for preliminary assessment and only refined methods are required for the critical elements.

5 Conclusions

Codes of practice currently show low uniformity on their requirements for fire design. In this paper, the governing aspects for fire design are reviewed and, on that basis, a consistent method for design based on a Levels-of-Approximation (LoA) approach is proposed. The main conclusions of the paper are:

1. Failures in fire are usually related to lack of deformation capacity of a member in a given structural system. Ductility requirements, not explicit in most codes for fire design, are thus instrumental for ensuring a satisfactory structural behaviour and sufficient strength.
2. The LoA approach is a suitable manner to write consistent and efficient fire design provisions. Low level LoA are based on geometric conditions but also include considerations on the ductility of the system. Higher-order LoA's have to account for heat transmission in concrete and lead to tailored results for special cases (structures of significant importance or particularly sensitive to fire).
3. Spalling is treated in a simple manner for low-order LoA by means of prescribing exposure conditions (related to moisture content) or detailing measurements (such as polypropylene fibres). Its analysis can be progressively refined (numerical methods, testing) allowing to analyse this phenomenon from a general perspective
4. Simple rules suitable for most cases can be identified for low-order LoA, that can be progressively refined (in higher-order LoA) for assessment of existing (non-conforming with low-level LoA) structures or for detailed analysis of peculiar or fire-sensitive structures

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