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DURABILITY PERFORMANCE OF CONCRETE STRUCTURES EXPOSED TO FIRE

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ABSTRACT

The present work looks into the developments related to understanding the impact of extreme heat on concrete and concrete-based forms of different nature. Being made of this material implies that any building should naturally resist fire; yet, concrete is, in eessence, is very complicated complex and likely to shift in terms of features when experiencing extreme heat. Fire, basically, reduces compressive strength, as well as spalling in concrete – the latter being described as forced removal of substances from the surface of any piece of fabrication. Despite vast amounts of data on these two effects, better structured investigations are to be carried out. The way buildings react to such fires in actual scenarios, in itself, is a different issue because of the interactions occuring among various components, effect of complicated small-scale events in theri entirety, and also the spatial and temporal changes in heat such as the cooling stage after the fire recedes. There have been advancements in the field of simulating thermo-mechanical patterns; however, how to handle intricate behaviours like hygral effects and spalling remains a question. On top of all this a major shortage exists in the amount of infoirmation related to actual structures for the purpose of validation, while precious other data can be obtained if we focus on behavior of concrete formations in such actual fire events.

Keywords: Concrete, Fire, High temperature, Modelling, Spalling, Review.

1. INTRODUCTION

Given its background, concrete, when exposed to fire, has usually been thought to be resilient as it is inflammable and serves as an obstacle. that limits heat and fire to where they are. The standards for design are in accordance to the findings in case of fire exposures [e.g. 1] and often explained as the necessary reinforcement sheet or cover; nevertheless, the overall application and efficiency in this reagrd is under question as heat patterns in actual settings differ from experimental ones. Specifically, the initial heat values may be faster, not to mention that actual fires possess very pecualiar cooling stages; these two settings exacerbate the amount of pressure on in situ formations, especially in confined spaces. For this reason, there is a lack of information as to the acutal perofrmance of concrete structures when exposed to real fire. Basically, concrete perofrmance is related with temperature-dependent specifications of any material. Because thermal diffusivity can be somehow small, as opposed to steel, higher temperature gradients often form inside concrete parts experiencing fire. Alongside increased thermal inertia, all of this implies that the central parts take longer to be heated. As a result, while the compressive strength diminshes quickly and detrimentally after a certain temperature – a phenomenon like the equivalent temperature for loss of steel strength - structural efficiency remains intact as long as the entire mass of the material achieves a critical temperature. Of course, such an event calls for examining the thermal reaction of the whole structure.

A seperate issue once concrete experiences fire is spalling [2], namely pieces of concrete seperating from the material owing to a decline in surface tensile strength. This is a product of mechanical factors inside the material caused by excessive heating or cooling – that is, thermal stresses – or due to a quick increase in the amount of moisture inside the concrete and adding to the pore water stress. Spalling can happen under many different situations with increased temperature gradients at the heating or cooling stages. Concrete behaves against fire relies not only on the details of composition, but also the actual nature of concrete, including factors like normal-strength, high-performance (HPC) or ultra-high-performance (UHP). Given this background, the present review primarily is to dealwith these two factors with a brief reference to the latter. Each topic will bedealt with thoroughly in the upcoming sections.

2. PHYSICAL AND CHEMICAL REACTIONS

There is a very complicated reaction between concrete and fire because of composition of the former and excessive thermal settings in the latter. In no way is concrete a homogenous substance, having a mixture of cement gel, aggregate and often steel or other material as reinforcement. These elements behave differently against high temperature, making the composite hard to determine as regards the overall performance [2]. In addition, reduced thermal conductivity can preclude the application of the so-called lumped parameter simplification, which is often applied to thermal analysis for metals like steel allowing to disregard in-solid thermal gradients. Quite often, design codes – such as BS 8110 [3]) – disreagrd these intricate points in temperature distributions and merely etermine a particular depth of concrete cover for the the reinforcement bars in composites to make up for insulation. In this way, the ambiguities related to thermal reaction are compensated for by means of thorough experiemtns in accordance to conventioal heating curves to be intorduced as fire-proof time, which is a function of thickness or cover, for various forms of concrete [3].

A series of both physical and chemical reactions take place in concrete when experiencing heat [2,4,5]. Among them, some can be altered by cooling, and others cannot be so – also known as non-reversible - and can greatly reduce structural strength after a fire. A majority of porous concretes contain liquid water, which starts to turn into vapor after 100°C, and then increase pressure inside the structure. Practically, the boiling point range is likely to change from 100 to almost 140°C given this pressure. Beyond the moisture plateau, once the heat approaches around 400°C, the calcium hydroxide inside the cement dehydrates and creates even more vapor, thereby seriously affecting physical strength within the structure. Among the other changes experienced by the material at these temperatures, we can refer to quartz- based aggregates which can grown in terms of volume because of mineral changes taking place around 575°C; another occurence is limestone aggregates gradually degenerating circa 800°C. Seperately, the thermal reaction of an aggregate is not that changeable, though the general reaction caused by such changes inside the concrete as a whole varies from the aggregate. To illustrate, differential expansion between the aggregate and the cement matrix ends up in cracks and spalling. Put together, such physical and chemical trnasofmrations can decrease the compressive strength. In actual settings, the critical temperatures for major drops in strength significantly rely on the kind of aggregate, average figures regarding sand light-weight concrete (650°C), carbonate (660°C) and siliceous (430°C). At lower temperatures, the impact of heat on the strength factor is also different and relies on not only the composition, but also the environment; for instance, how much the concrete is sealed by moisture [2]. Another factor to consider is the effect of concrete strength, with the hot strengths of UHPC concretes diminishing more in comparison to other types [2]. However, as we stated earlier, such temperature-related factors as a whole can merely offer indirect clues as to the degree of fire- proofness in concrete structures; this is because of sharper temperature gradients categorically appearing inside the material. Structural collapse usually takes place only once the effective strength of a steel reinforcement is lost as a result of extreme heat.

The intricate physical and chemical factors causing changes in the concrete upon fire are of major concern among experts studyingthem for years now. Regretably, a majority of these attempts are merely limited to specifc and predefined heating regimes, those not quite in contact with acutal fire incidents. For example, some these attemps have included the temperature-time curve used in standard fire tests; slow heating which causes diminished internal temperature gradients; and applying alternative temperature-time relationships only ideal for certain application. For this reason, the overall impact of both physical and chemical transformations as reagrds the thermal gradients in case of fire remains, to a large extent, an unexplored topic. Given this fact, major fields to deal with include organized and sytematic changes of thermal exposure, both at the surface and in-depth within materials, as well as interpreting such results related to possible settings in real-life fire incidents – thait is to say, finding out more about the worst-case fire incidents. Post-fire, the transformations within the structural features cannot be undone in the case of concrete; whereas, in the case of steel, cooling can usually help to retain the material back to the original status. The reason for this is the inevitable changes caused within the physical and chemical characteristics of cement which serve as markers for maximum exposure temperatures in accrodance to post-fire tests on the concrete surface [6,7]. Let us not forget that, under certain settings, a concrete structure can be significanly weakened once fire breaks out, regardless of whether there is visible damage or not.

There are numerous conceptual approaches applicable for the mechanical perofrmance of concrete exposed to high temperature; some of them have been reviewed by Li & Purkiss [8], specially the ones created by Anderberg & Thelandersson [9], Schneider [10], and Khoury & Terro [11]. The ultimate goal has been to set up a common approach for definitive element analyses within structures. It has been stated that such thermo-mechanical patterns and models tend to be free of the limits exerted on concrete in 4 seperate ways, namely „free thermal strain‟ caused by temperature changes; „creep strain‟ caused by microstructural changes inside the material; „transient strain‟ as a result of chemical transfomrations within the concrete; and, lastly, stress-related strain‟ due to forces exerted from the outside environment. The simulations reviewed by Li & Purkiss all deal with these factors in a separate way [8]. To elaborate, "free thermal strain" alone is a function of the temperature of the concrete member, whereas creep, transient and stress-related strains are those related to stress, temperature and time. As a result, it is a challenge to try and differentiate the strains undergoing change when tests are conducted. To tackle this shortage and handle the issue, certain models can collect two or even all three of these strains into one effective term. Commonly, transient creep strain is the one that combines creep strain and transient strain – otherwise regarded as load- induced thermal strain or LITS for short. How significant it is to refer to this strain – one that, in particular, addresses concrete amongst other materials and can encompass elastic strains as well – has also been reiterated by certain scholars, among them Khoury [2,58] and Nielsen [12]. Indeed, the common notion is that transient thermal creep, if present, is behind concrete not degenerating entirely beyond 100°C of temperature because the effect, in itself, can offer a certain degree of relaxation within the material [13], thus reducing stress gradients caused by thermal incompatibility and temperature gradients. In addition to this, past the 100°C threshold, LITS relies primarily on temperature, and not time necessarily, thus making it more likely to be modeled easily [2].

Based on the studies of the stated scholars, Li & Purkiss formed an additional approach applied to illustrate the role of transient strain [8], by revealing that those models excluding thisfactor are unconservative asreagrds high temperatures; yet, in lower temperatures transient strain seems to lose its impact. Another point of that study is the full stress-strain curves offered in EN 1992-1-2 (the structural Eurocode for concrete design [14]) being unconservative again at elevated temperatures in comparison to the figures appearing in the models examined. In the ned, concrete structures can collapse and fail due to various reasons [2]. In case of load-bearing reinforced slabs, should the strength of the steel reinforcement diminish as a result of heat, there can be bending or tensile strength failure. This firmula is customarily attributed to mid-span deflections of L/30, where L is the span. Reinforced structures can collpase in other cases, where there is no more bond between the concrete and the reinforcement bars along with concrete tensile failure. Shear or torsion failure may as well be affected by concrete tensile strength, but these tweo have not been thoroughly defined at the test level. Ultimately, compressive failures often follow temperature-related declines in the compressive strength of the concrete occuring within the compression area.

Stated n practical terms, a large number of such settings can be tied to structural performance within the member in situ – in other words, as regards the restrains and supports rendered from other parts of the structure; hence, these factors have to be addressed all at the same time. As a result, it is a challenge to try and differentiate the strains undergoing change when tests are conducted. To tackle this shortage and handle the issue, certain models can collect two or even all three of these strains into one effective term. Commonly, transient creep strain is the one that combines creep strain and transient strain – otherwise regarded as load- induced thermal strain or LITS for short. How significant it is to refer to this strain – one that, in particular, addresses concrete amongst other materials and can encompass elastic strains as well – has also been reiterated by certain scholars, among them Khoury [2,59] and Nielsen [12]. Indeed, the common notion is that transient thermal creep, if present, is behind concrete not degenerating entirely beyond 100°C of temperature because the effect, in itself, can offer a certain degree of relaxation within the material [13], thus reducing stress gradients caused by thermal incompatibility and temperature gradients. In addition to this, past the 100°C threshold, LITS relies primarily on temperature, and not time necessarily, thus making it more likely to be modeled easily [2]. Based on the studies of the stated scholars, Li & Purkiss formed an additional approach applied to illustrate the role of transient strain [8], by revealing that those models excluding thisfactor are unconservative asreagrds high temperatures; yet, in lower temperatures transient strain seems to lose its impact. Another point of that study is the full stress-strain curves offered in EN 1992-1-2 (the structural Eurocode for concrete design [14]) being unconservative again at elevated temperatures in comparison to the figures appearing in the models examined.

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1. SPALLING

A very complicated and, thus, highly obscure aspect of concrete performance as regards the case of extreme heat and fire is a concept known as „explosive spalling" [2,16], which is sometimes understood to take place merely at such elevated temperatures; nevertheless, there have been reports as well of preliminary phases of fire [17] and even in lower degrees as 200°C [18]. In serious cases, spalling is likely to cause major a decline in terms of structural strength of reinforced concrete owing to the heating of the steel armour. Apart from this, spalling can greatly deteriorate – even remove entirely – the cover section of the concrete on top of the reinforcement bars and, hence, leave the remaining areas exposed, eventually causing a major declines in strength and the overall mechanical properties of the structure. Apart from the impacts stated above on the physical proeprties within membranes and fomrations, spalling reduces cross-section concrete parts which support the exerted loading; in this way, adding further to the stress sustained by the rest of the structure. This occurence is, in particular, important since the phenomenon can occur even at much lower termperatures than anticipated and prior to any such dire consequences are detected within the rest of the structure. How spalling takes place is, in the general sense, caused by advanced thermal stresses originating from quick heating or major accumulation of pressure inside porous sections of the concrete. Such pressure cannot be withstood and cancelled out by the structure because of the presence of moisture in the form of evaporation. Overall, this chain of reactions cause the formation of cracks and pieces of concrete seperating from the member surface layers. In detail, the primary requirements for spalling are as listed in the following: Amount of moisture up to a minimum of 2%, and steep temperature gradients presernt inside the material, in which latter case figures around 5K/mm can be an approximate value, whereas at about 7-8K/mm spalling can almost certainly take place [19]. Temperature gradients rely not just on the gas-phase temperatures, but on the heating rate; therefore, one cannot accurately detemrine a certain threshold temperature and, instead, a similar or close ratio may be established as reagrds the heating rates –mainly around 3K/min [2]. Such decisive figures for the event of spalling, nonetheless, are also influenced given the nature of the concrete and its properties, namely material strength as well as whether there are any form of fibres [2] present, as discussed further below.

Apart from this, extensive studies have been underway concerning the posibility of including different kinds fibres within the concrete sections in order to make up for the spalling impact. In this respect, certain works [20-24] take into account polypropylene to be used within the concrete matrix based on the assumption that once exposed to heat, the polypropylene fibres inside the concrete can melt and, in this way, form exit routes nside the material so that the water vapor and any other forms of gas can escape, thus helping to alleviate the pressure induced through accumulation. Arguments, though, ahve been raised as regards the choice of mono-filament or multi-filament fibres in order to mitigate the occurence of spalling [25]. Others have also proposed melted polypropylene fibres, which are cpable of creating a form of obstacle against the movement of moisture any further inside the mateiral, thus mitigating the fomraiton of pressure in deeper sections and, rather, allowing for it to escape [21]. In contrast to all these benefits, polypropylene fibres can also create a system of crack formation at the deeper levels inside the material, preventing surface-level spalling but causing other unwanted structural deficiencies within [21]. Certain experiments have tried to add steel fibres within concrete material [25] in accordance to the notion that they can add to ductility and make the concrete stronger against high internal pressures. These studies, though, have not yet come to any definitive results [25]. Lately, applying high-strength (or high-performance concrete has been a subject of interest to many in the industry and reasech community since the material enjoys a significant amount of compressive strength in comparison to normal-strength concrete, yet with much reduced porosity and moisture absorbance. These qualities might, as a whole, decrease the water content inside the material, but they can also – naturally – restrict its moving out in the form of evaporation in case of extreme heat. There have been debates over high-strength concrete being more susceptible to spalling given the reduce porosity and, henceforth, its added potential for high amounts of pressure forming inside the membrane or structure [20]. On the other hand, studies also confirm that such occurences are not quite frequent, with some even pointing to added spalling resistance owing to this features [21] and the fact that overall and advanced tensile strength may positively cancel out the forces contributing to spalling. Laslty, it has to be remembered that although tere are major obstacles concerning the intricate aspects of spalling, its simulation today is much more successful than before [2,26,16], naturally requiring more effort in future.

3. CRACKING

This phenomenon how it takes place are often thought to be identical to the ones that trgiger spalling formations. Thermal expansion and dehydration in the structure caused by extreme heat can pave the way for fissures and cracks inside the material instead of – or at the same time with - explosive spalling. Such cracks and openings form pathways and routes allwoing the heat to enter further inside the reinforcement bars and, in thsi way, generate even more thermal stress and fissure-formation. In some case, these fissures can make room for the fire to further move toward the adjoining sections ofthe structure. In this respect, Geogali & Tsakiridis [27] conducted a research on the cracking phenomenon taking place within concrete building that experience fire events, focusing primarily on the depths to which fissures and cracks penetrate the structure. The results point to this depth to be in conjuction with the temperature, as well as cracks overlall advacning well inside the concrete sections. Significant damages were mainly restricted to the surface area surrounding the source of the fire, whereas the cracks and the resulting material discolouration provided clues as to the material around the reinforcement heating up as much as 700°C or more. Those cracks advancing further than 30 mm within the structural depth were seen to be caused by brief heating/cooling effects as the fire was eventually being put out. At this stage, stress conditions and their significance as regards concrete structures are not to be understated, and compressive loads caused by thermal expansion can even turn into useful mechanisms that help to compact the material and, thus, prevent any form of fissure or crack development [2]. The outcome is very limited degeneration of compressive strength and elastic modulus compared to those sections that bear lower loading values.

4. USE OF SUPPORTING MATERIALS

There have been studies carried out on the impact of embracing concrete sections within differnet kinds of material so as to see whether this develops spalling resistance to any significant degree [28]. According to the results of these efforts, metal fabrics for wrapping positively helped against spalling, whereas carbon fibre-based or glass fibre-based fabrics did not yield much of a benefit. These experiments showed to offer reduced or no spalling in case of polypropylene fibres added within the concrete mixture [22]. Steel fabric also decreases spalling as it offers lateral confinement pressures to the structure at degrees much higher than the internal vapour pressure – the main cause of spalling, as stated before. Carbon and glass fibre fabrics are less efficient in this repsect since their bond strength is likely to decrease in elevated temperatures, in turn decreasing the fabric‟s potential to protect and cofnine the concrete membrane. The method has been shown not to induces any cracking within the deeper sections of the structure.

5. REINFORCEMENT BEHAVIOR DURING FIRE EVENTS

Steel behavior in the event of fire is believed to be much better than that of concrete as the steel strength at any temperature may be assessed with a fair degree of assurance. The common belief is that these bars are to be safeguarded against contact with heat excedding 250-300°C. The reason for this is because steel bars possessing less carbon exhibit a feafure known as „blue brittleness‟ at temperatures ranging between 200 and 300°C. Both concrete and steel share identical thermal expansion properties until as high as 400°C; nevertheless, beyond this value the heat can cause major expansion in steel bars as oposed to the concrete slabs. Should the heat levels achieve approximately 700°C or more, then the load-bearing potential of any steel reinforcement can be diminished by as much as 20% of the original design value. Apart from these factors, steel reinforcement may as well impact significantly the movement of water inside heated concrete sections, there by forming impermeable areas, from where water cannot escape in any way and, thus forces it move around the bars, add to the pore pressure in certain sections of the concrete and, eventually, trigger further spalling in those sections. Conversely, such sections where there is confined water contents may as well change the direction of heat flow clsoe to the reinforcement bars and possibly cause a decline in the temperature values inside the concrete [29]. A major portion of a certain has been focused on applying glass or carbon fibre reinforcement to replace steel components in concrete [30-34]. A great deal of the motivation behind this work was the absence of any data concerning fibre reinforced plastic reinforcement - or FRP for short – in case of elevated temperatures. Nonetheless, a great deal of the related experiments have pointed to the adequate FRP covering for reinforcements leading to ancreased fire-resistance [30,31]. Addirtionally, externally- bonded FRP has been shown to add strength to the structure at issue. Under such circumstances, supplying fire-proof content is another major field to be further investigated [35].

6. COMPOSITE STRUCTURES

A popular means of making floor slabs in buildings is well known to be „composite construction‟, in which approach concrete slabs are fomred on steel beams. Slab framework in this way are profiled metal sheets – otherwise named „decking‟ – to cover the area between the beams. Seperately, shear studs are then welded on top of the steel beams and through the profiled decking in order to make room for mechanical bonds to get shaped between the concrete and the steel sections and, ultimately, let the beam and the slab to serve in the form of one element for further strength. Steel deckings, in this way, remian in their position indefinitely once concrete is added. Steel reinforcements are further supplied on top of the profiled decking. A great deal of research has been conducted concenring fire behavior of composite steel and concrete formations; to provide an example, the Cardington tests contained a series of full- scale fires on a steel-framed structure with composite concrete making the floor slabs. Such structures are seen to be highly fire-proof far more than it was originally anticipated [36]. The reason behind such advanced perofrmance is, to a large extent, due to the slabs enjoying the property of acting as a tensile membrane thanks to the steel reinforcement suppliedon top of them over the decking section, thus permitting the load to be redistributes by means of the structure once the steel properties being to deteriorate. in certain occasions, such an occurence can bring about fewer conditions to fire-proof the steel sections within the structure; in particular and in conventional terms, the secondary beams.

7. FIRE RESISTANCE

Similar to other sections of a structure, evaluating the behavior of concrete membranes is conventionally performed in relation to common heating curves formulated fire durability experimental furnaces [37-39,60]. Such curves and regimes are explained solely in relation to temperature-time curves, previously regarded as a representaion of fire formation in a standard living room space, and defined mainly in similar forms in a number of standards, at the internatioal - that is, the ISO-834 fire curve [1] – and domestic – that is, the BS-476 curve - level in the United Kingdom, and as per the ASTM E-119 in the United States. Apart from this, conventional fire curves are present and applied to simulate temperature changes in other theoretical settings [2]. To illustrate, the „hydrocarbon curve‟ [40] has been popular in the chemical processing sector to simulate fire formation ignited by liquids. The curve shows a far more speedy development stage and elevated temperatures exceeding 1000°C taking place in a matter of the first 20 minutes after ignition. In Holland, the Rijkwaterstaat and TNO have set up a conventional fire curve (RWS) to rperesent temperature changes within a tanker or large transportation truck

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inside a tunnel [41]. The curve shows very speedy temperature increases that reach up to 1350°C in the course of 60 minutes. The same curve has also been applied to test non-tunnel structural sections.

Whereas such experimental techniques enjoy the benefit of offering some standardisation for the intended heating regimes, they lack in serious respects that are coommonly acknolwedged by experts [37-39]. To start with, despite temperature increases that appear conventional within furnace-controlled environments, the real effect of heating on a structure relies on many other factors, among them the optical attributes of the furnace gases themseleves,along with the thermal response from the structure. Next, experiments offer insufficient data as regards the potential behavior of structural elements in situ – that is to say, bearing in mind the exchanges taking place among various components within the same structure, the restraint factor, and so on. A third point addresses the possible presnece of gradients in the thermal exposures, even inside the "uniform heating" settings of fire resistance furnaces [42]. In these scenarios, yet higher and steeper gradients can be witnessed in all-out and fully-spread compartment fires [43]. The impact on the structural behavior of spatial non-uniformities during heating still remains an unclear point despite the long acknowledgement related to spalling and its ties with such impacts. A final point is that conventional curves do not consider the highly debateable post-fire cooling step [44]. The likely importance of the said stage on the behavior of concrete has been shown with experiments conducted on concrete segments at the Hagerbach test gallery in Switzerland [45]. Accoridng to the reports, while a concrete specimen could stand temperatures as high as 1600°C for 120 minutes and remain failure-free, within 30 minutes past the cooling stage that same specimen failed explosively. For now, it cannot be determined - in case of most settings – the extent of spalling that occurs in actual construction fire incidents and as the outcome of cooling, and not heating. Despite major studies invested to figure out the performance of steel structures when cooling occurs, there has been little effort made in case of concrete structures.

Based on the information stated earlier, conventional fire experiments may simply model a finite scope of heating settings. Lately, debates have been focused on the various reaction mechanisms toward fire by concrete segments in case of the so-called „short hot" fire incidents, as opposed to „long cool" fires. Though a great many of such settings are treated using what is knowns as „parametric curves" [46], a majority remains under the influence of standard furnace applications. Furthermore, approaches to set up a relationship between conventional experiments and acutal fire performance have been roiughly designed mostly involve steel segments – again, not concrete or thermal insulation [47]. The so-called „short hot" fires cause major thermal pressure to structures, yet within very short spans; on the other hand, while along cool" fire is in progress, the highest temperatures can be low, though given the extent of the period that the fire lasts, concrete sections are likely to experience heating at far deeper levels than expected. Discussions as to which setting can be more destructive to the concrete are still in progress [48]. In this respect, Lamont et al. [48] took on the task of simulating finite elements in such fires for composite steel and concrete formations; accordingly, whereas there is no major study so far to deal with pure concrete structures, most of such conclusions obtained in similar scenarios can be applied likewise. Various degrees of fire exposure, in these tests, were simulated by applying a steady fire load of 250 MJ/m^2 implemented with various opening areas to simulate actual settings within actual fires, yet varying in terms of ventilation failure. The literature, though, offers no specific validation in accordance to the outcomes of these efforts.

In further detail, given the very nature of conventional fire experiments carried out in furnaces, the movement of heat in between structural sections being tested may vary greatly depending on the nature of the section or component under investigation.To illustrate this fact, a steel beam and a concrete slab exposed to identical furnace settings can behave in contrasting ways, thereason being that the thermal conductivity of steel far exceeds that of concrete. While experiments are in progress, the net heat transfer from the furnace gases to the member surface can be many folds that of the concrete sections. For this reason, once the preliminary rapid heating of the surface of the slab is done, similar standard methods can heat up the same beam to much more elevated net heat flux comparedto a concrete beam [42]. A different method to determine the phenomenon of heating can be to adjust the steady exposure values of temperature. Related to this, Hertz & Sorensen [20] created a bench-scale experimental approach to examine the occurence of spalling upon concrete cylinders. For this purpose, a furnace temperature of 1000°C created surface temperatures reaching 800°C in a period of 20 minutes. In practical terms, such an approach can be applied to see the impact of not just exposure temperature, but the heating rates as well.

8. WHOLE-STRUCTURE PERFORMANCE

Although knowing about the bahavior of each concrete section in case of fire is an important task, the perofrmance of identical structural elements within a full structure may be affected largely based on individual segment reactions. To offer an example, thermal enlargement of such members exposed to heat can cause certain forces to be cast upon the cooler parts owing to differential expansion, with compression forces inside the heated parts caused as a result of the limiting forces from the remaining parts of a structure. The impacts of thermal enlargement, for quite a while, have been known concenring steel and composite members [49], though unknown when it comes to concrete structures; still, the occurence is likely to cause failure in such concrete structures when fires break out, and its fucntion in real collapses due to fire is under discussion by experts [15]. In the same way, however, one has to understand that the scenarios in which a single concrete member has collapsed, the entire structure can still remain unharmed owing to the inevitable redundancies along with load redistribution. Simulations have been underway reagrding different individual concrete elements, among them columns, in case of fire [50]. Specifically, these members are applied to make comparisons among the forecasts in accordanceto the structural Eurocodes, andto verify the results concerning actual concrete columns and their performance when an all- out fire experiemt is done. Other efforts have been made to address the boundary settings of these column alongsidethe impact of heating on the concrete itself [51] to offer better estimates and simulations resembling fires impacting full structures. The latter iinitiative is specifically paramount as there is a need to establish a relationship between the perofmrance of structural sections and the entire structure itself , as well as to investigate the imapct of one member on the neighboring structure once heated.

Such experiments reveal that other forces that came to be were rather insignificant - about 15% of the design load for columns. Also, the columns undergoing tests measured 125mm x 125mm cross-section x 1.8m high with 108 N/mm2 high-strength concrete – which is a relatively small section in comparison an, hence, unclear as regards the related data being applicable to bigger sections or to those having normal-strength concrete. Overall, the research has relied on additonal work in the future. Major data concerning the impact of fire on entire structures comes from experiments conducted at Cardington by the Building Research Establishment (BRE) [17,15,52]. One of the entire structures within the Cardington laboratory comprised a seven-storey concrete building, on which a fire experiment was carried out by applying a fire load from wood cribs in an open compartment on the ground floor, surrounding a high- strength concrete column. The resulting thermal exposure caused by the fire may not have been substantial, though it managed to highlight the column behavior quite remarkably with hardly any visible failure; the column had polypropylene fibres inside which could have brought about this result. Nevertheless, unanticipated and excessive levels of spalling could be seen within the ceiling section, which was formed out of ordinary--strength concrete. The section, yet, stayed unaffected entirely, perhaps as a result of the compressive membrane action since enlargements within the concrete slab section had been limited thanks to the cold sections around the structure. This helped the load to be maintained by the compressive strength of the concrete. Compressive membrane action of this nature occurs only once there are rather insignificant dislocations. In major displacements, however, the tensile membrane action factor can also make up for the task of maintaining the floor slab while the reinforcement itself limits slab dislocation. Systems of this nature, though, depend mainly on the support of reinforcing bars keeping adequate strength. As regards the Cardington experiment, the near-surface reinforcing bars cannot be creditted with retainment ofany major values of strength because they are directly in contact with excessive heat caused by the scope of spalling, thus making it unknown as to the way the slab could have reacted at such advanced degrees of displacement. The information supplied by Cardington is applied as input for a limited element model to make a series of theoretical assumptions reagrding concrete behavior in case of fire, disregarding along the way the role of spalling [17]. Based onthe findings, additional work is needed to see the impact of fire on entire constructions. One more beneficial source of data concerning the enitre strcuture bnehavior comes to us based on the the patterns of actual fires incidents – a topic that is recently receiving much attention and remains active, in particular, the case of the Windsor Tower fire in Madrid (February 2005) [53] as well as similar historical fires [15] In this case, the primary obstacle is how to simulate the fire settings that could have actually occured, thus the need for more developed simulation mechanisms and other interpretations of different kinds of fire records, including videos. Better registration of concrete behavior in other cases can, therefore, help us to promote our knowledge in the field.

9. DETAILED MODELS

A thorough study of structural concrete required detailed analysis, in which case available systems can barely satisfy the need and computational simulations are the only way out for realistic results. Should we merely depend on complicated numerical data, then the constitutive relationships based upon which the y operate also have to be precise to offer all of the test-proven phenomena. In additon, experts particiapting in these efforts require extensive knowledge of the physical intricacies within them so as to offer sound judgements during the analysis, design and assessment steps. A number of commercially-available „Finite Element Analysis" packages can expalin the thermo-mechanical performance of reinforced concrete. Yet, except for a number of cases, these assessments are often inconclusive since they tend to over-simplify complicated issues like concrete simulation, not to mention the absence of sufficent algorithmic certainty. This simplification is done by means of using a temperature dependency for the material properties; yet, such an attempt does not fully address complicated coupled processes leading to these phenomena, thereby rendering these codes and standards ineffective for intricate simulations of concret performance.

The actual performance of concrete when exposed to extreme settings also depends on the background of multi-axial stress state, temperature and moisture content [2,26]. Previously, insufficient simulations of complicated coupling relatedto these factors has caused over- simplification again and again and, thus, has been unsuccessful in offering sound quantitative forecasts for performance. Indeed, concrete in these settings hasto be regharded as a multi- stage system with empty spaces being in part filled with liquid and, in other parts, with gases containing dry air and water vapor alongside each other. In order to effectively model structural concrete exposed to numerous loading scenarios, simulations have to include coupled heat-mass transfer and mechanical analysis. Three primary physical processes worthy of attention in these coupled settings are, hence, mechanical, thermal and hygral. Former attempts to simulate, as a whole, offer the thermo-mechanical reaction of concrete via generalizing the isothermal patterns to include thermal dependency as well. When it comes to a majority of industrial finite element standards, the mechanical features like strength and stiffness simply address temperature and leave aside the irreversible transfomrations experienced by the material properties themselves. An advanced thermodynamically stable simulation was proposed by Stabler [54], in whose work the impact of temperature appears in the assessemtns by means of applying a thermal damage model, with the main thermal and mechanical formulations dealt with in an entirely coupled style. Nonetheless, hygral considerations and transient thermal creep remained outside, which is not ideal as they are major phenomena and critical for investigating the exact reactions to heating, as stated earlier. Tenchev [16] created a numerical approach for heat-mass transfer where the entire stages are simulated thoroughly, yet again leaving out the mechanical coupling. This issue is, by nature, an extension because since dehydration and mass transport due to heat cause major modifications in the mechanical material properties, leading to decohesion and stiffness loss. A handful of fully-coupled hygro-thermo-mechanical simulations are available in the literature, with exceptions that include Khoury et al. [26,2,57], Grasberger & Meschke [55] and Ulm et al. [56]. The stated works are not cost-effective for implementation as full-scale. models.

10. CONCLUSIONS AND FUTURE WORK

Concrete performance when exposed to fire, for now, remains a questions mark and additioonal work is to be carried out in just about all aspects in this matter. The concrete reaction to extreme heat is mainly complicated; for instance, degradation of the physical features can occur to a large extent based on the mix, moisture, and environmental settings that include maximum fire temperature and its period. Organized research, thus, is called for to address the impact of various heating regimes on concrete-based material and structures. At this stage, a pressing issue is raised in connecting such details to the behavior of entire structures in actual fire events. Although satisfactory developments have taken place as regards simulating the mechanical behavior of these structures, specially related to the LITS role, applying intricate moldes for spalling predictions lack enough study efforts. In addition, our ability to forecast structural behavior – which can possibly play a separate role – remains rather undeveloped. The past has taught the industry that only primitive efforts have been made to explain fire scenarios, important temperature-time curves and/or homogeneous temperatures, all of which items are too simple representations of actual fire settings and conditions. Accordingly, far more extended studies are needed for the impact of temporal and spatial changes in the heating regimes, as concerns a wide spectrum of concrete compositions. Such efforts, naturally, call for additional testing of entire structures when real-life fires break out, so that we can see holistic patterns such as the interactions between various sections of the same structure to help verify complicated computer simulations. More detailed work is also necessary for concrete behavior in real fire cases, which are of significant contribution to our knowledge of real-world scenarios.

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