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Structural Behaviour of Concrete Walls during or after Exposure to Fire: A Review

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Abstract: Reinforced concrete walls form an integral part of the structure of many buildings. They support both vertical and lateral loads and provide fire separation between different compartments within a building. During a fire, a concrete wall must: maintain its structural adequacy, provide temperature insulation between the building compartments, and remain free of excessive cracking or deformations that would allow the passage of flames. After a fire, it is critical to know the vertical and lateral capacity of the fire-damaged concrete wall to assess the safety of the building. Current building codes address the design of concrete walls for fire by specifying minimum thicknesses of walls based on required fire ratings. As building codes move towards performance-based design for fire, it is important to provide engineers with a performance-based method for designing concrete walls to resist fire. This paper summarizes and provides a critical review of existing experimental and analytical research addressing the effect of fire on concrete walls. The completeness, practicality, and accuracy of the existing literature is reviewed for the purpose of determining future research needs.

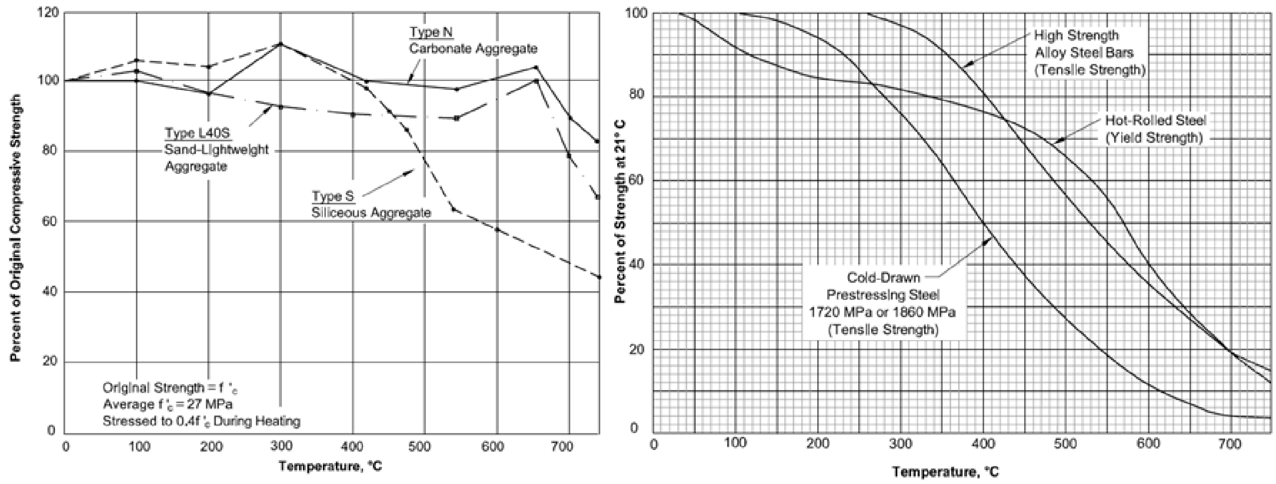
1 Introduction

Reinforced concrete structures have become an increasingly popular method for providing fire-resistant structures over the past years. Reasons that concrete is so effective as a fire-resistant building material include: being a non-ignitable material, having a low thermal conductivity, the ability to provide structural integrity, and the ability to retain a good deal of structural adequacy during a fire (CPCI 2007). One of the integral parts of such concrete structures is concrete walls. Concrete walls support both vertical and horizontal loads as well as provide temperature insulation between different compartments within a building. Engineers currently design concrete walls to resist fire by choosing minimum thicknesses and concrete covers for walls from building codes. However, building codes are moving towards performance-based design for fire and it is thus important that engineers be provided with an accurate and efficient performance-based method to design concrete walls for fire. The goal of this paper is to provide a critical review of available literature pertaining to performance-based design of concrete walls for fire and the assessment of concrete walls after fire.

2 Effect of Fire on Concrete

2.1 Material Properties during Fire

Elevated temperatures experienced during a fire cause a significant degradation in critical material properties of reinforced concrete structures, including concrete compressive strength (Fig. 1a), concrete modulus of elasticity, yield strength of steel reinforcing bars (Fig. 1b), and bond strength between reinforcing bars and concrete (Youssef and Moftah 2007).



a) Concrete Compressive Strength **b) Steel Yield Strength**

Figure 1: Effect of Elevated Temperatures on Reinforced Concrete Materials (CPCI 2007)

Elevated temperatures further affect the material properties of concrete by introducing fire-related strains in the form of thermal strains and transient creep strains. Thermal strains result from the unrestrained thermal expansion of concrete caused by elevated temperatures (Youssef and Moftah 2007). “Transient creep strains” is a term used to describe a marked increase in strains during initial heating (Purkiss 1996). Several models have been developed to evaluate transient creep strains, including models by Terro (1998) and Anderberg and Thelandersson (1976). Incorporating these models into a stress-strain curve relationship requires iteration. A method to eliminate the need for these iterations has been proposed by Youssef and Moftah (2007) based on work done by Collins and Mitchell (1987). This method accounts for transient creep by shifting the strain at maximum stress by the transient creep strain.

2.2 Spalling

Elevated temperatures further affect concrete through a phenomenon known as spalling. Spalling is characterized by the breaking off of pieces or layers of surface concrete. Spalling occurs in three different forms: aggregate spalling, corner spalling, and explosive spalling (Deeny and Stratford 2008). Aggregate and corner spalling occur during the decay stages of a fire, and thus do not significantly affect structural performance during fire. Explosive spalling involves the ejection of pieces of concrete from the surface at high velocities. Because this type of spalling generally occurs during the early stages of a fire when the heating rates are high, it can have a significant impact on the structural performance of concrete in fire.

Much disagreement exists in the literature as to the exact mechanism of explosive spalling. One of the widely accepted mechanisms relates to pore pressures induced by heated water vapour in the concrete (Dwaikat and Kodur 2009). If pore pressures exceed the tensile strength of concrete they in theory cause local failure of the concrete. However, it has been pointed out that no pore pressures that exceed the tensile strength of concrete have yet been measured (Deeny and Stratford 2008). A second mechanism by which spalling is thought to occur relates to thermal stresses (Deeny and Stratford 2008). High thermal gradients caused by the heating of the concrete cause compressive stresses near the surface due to restrained thermal expansion and tensile stresses further beneath the surface where temperatures are not as high. It is likely that the actual phenomenon of explosive spalling is caused by a combination of both pore pressure induced spalling and thermal stress induced spalling.

2.3 Material Properties after Fire

The material properties of both concrete and steel reinforcement after exposure to elevated temperatures are different from values during exposure to ambient or elevated temperatures. The post-fire concrete compressive strength and its modulus of elasticity are lower than pre-fire values but higher than during fire. The ability of concrete to recover its strength and stiffness properties after fire is a function of the fire temperature, the heating rate, and the cooling rate (Lee et al. 2008). A higher maximum temperature, heating rate, or cooling rate all cause both a lower residual concrete strength and residual modulus of elasticity. Lee et al. (2008) suggested that the water permeability of concrete can be used to determine the residual properties of concrete after exposure to fire as it is increased by exposure to fire and is a function of maximum temperature, heating rate, and cooling rate.

The post-fire yield strength of steel reinforcing bars is also different than before or during exposure to fire. The ability of the reinforcing bars to recover their yield strength after exposure to fire is a function of the maximum exposure temperature, the cooling rate, and their type (Felicetti et al. 2009). A higher maximum exposure temperature or a higher cooling rate causes a decrease in post-fire strength. It has also been shown that the type of reinforcing bars has a significant effect on their post-fire properties, with carbon-steel bars recovering more strength than quenched or self-tempered bars (Felicetti et al. 2009). Another important post-fire property of steel reinforcing is ductility. Bars that are exposed to high temperatures and cooled rapidly are shown to exhibit a brittle failure mode (Neves et al. 1996).

3 Design of Concrete Wall at Ambient Temperature

The different types of loads that must be resisted by concrete walls are illustrated in Figure 2.

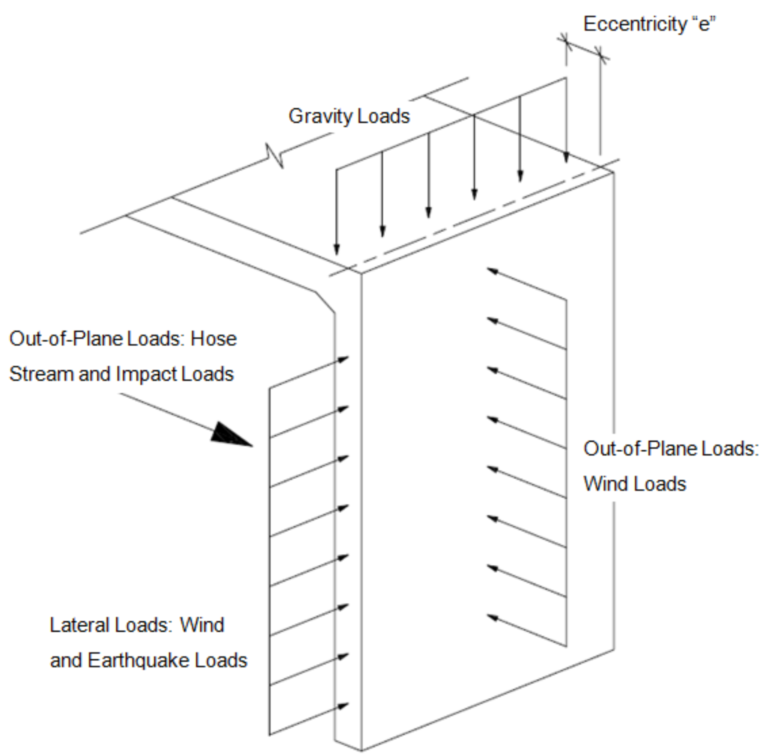


Figure 2: Loads Resisted by Concrete Walls

3.1 Gravity Loads

Reinforced concrete walls are designed to resist the effect of gravity loads and their eccentricities. This design is similar to the design of slender columns. Generally walls that are greater than 210 mm thick are reinforced with two steel meshes placed not more than one third of the wall thickness from each side of the wall (CSA A23.3-04 2004). The vertical reinforcing bars resist the applied moment due to the load eccentricities. The horizontal reinforcing bars resist shrinkage and shear stresses and tie the vertical reinforcing bars together.

3.2 Out-of-Plane Loads

Exterior walls are designed to transfer wind loads applied to the exterior facade of the structure to lateral supports that include floor and roof diaphragms and/or perpendicular columns or walls. Both interior and exterior walls may also be required to resist differential pressure loads. Concrete walls must also be designed to withstand a hose stream load from fire-fighting efforts (CPCI 2007). Design to resist these loads is similar to the flexural and shear design of reinforced concrete slabs.

3.3 Lateral Loads

Walls designed to act as shear walls must resist the effects of earthquake and wind loads. The effect of the lateral loads is transferred to the shear walls by the floor and roof diaphragms. Individual walls or interconnected systems of shear walls that resist such loads are designed as cantilevered beams with a fixed connection at the base of the wall.

4 Design of Concrete Wall for Fire

4.1 Fire Ratings

A fire rating is the length of time that a structural member or system must provide adequate fire resistance when exposed to a standard fire such as the ASTM E119 standard fire curve, Figure 3.

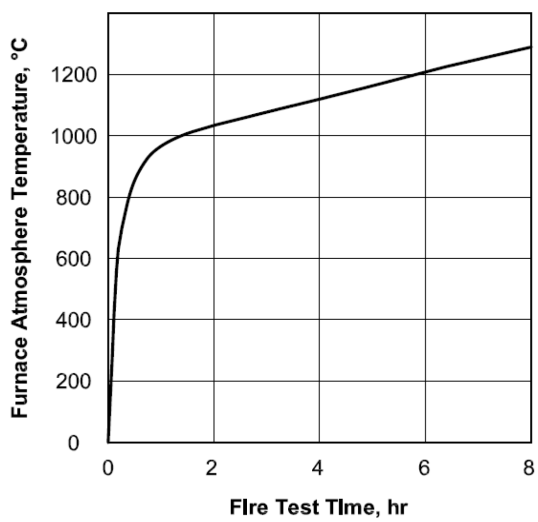


Figure 3: ASTM E119 Standard Fire Curve (ACI 216R-89 1989)

Generally required fire ratings are determined by consulting the building code having jurisdiction and are based on occupancy levels, building size, location of the building relative to the property and adjacent buildings, and materials separated by the fire walls (ACI 216R-89 1989).

4.2 Three Requirements for Fire Safety of Walls

Current design guidelines for fire safety, including the CPCI Design Manual (2007), the Eurocode (2004), and the ACI Guide for Determining Fire Endurance of Concrete Elements (1989), specify three criteria for fire resistance, all of which are directly applicable to reinforced concrete walls. The three requirements are temperature insulation, structural integrity, and structural adequacy.

The first criterion for fire resistance is that a concrete wall provides adequate temperature insulation between its exposed and unexposed sides. This is to prevent materials on the unexposed side of the wall from igniting due to exposure to high temperatures. Generally this requirement is met by limiting the maximum temperature on the unexposed side of the wall to a certain value. For example, ACI 216R-89 limits the rise in temperature on the unexposed side of the wall to 139 C with a maximum temperature not exceeding 181 C.

The second criterion for fire resistance is that a concrete wall must prevent the spread of flames or toxic gasses through cracks or fissures in the wall. This criterion is again designed to prevent materials on the unexposed side of the wall from igniting, in this case from gasses or flames instead of high temperatures. This requirement is evaluated by placing cotton waste on the unexposed side of the concrete wall during a fire test. If the cotton waste ignites at some point during the fire test, this criterion is reached.

The final criterion is that a concrete wall must resist the full effect of all specified loads, including hose stream loads, throughout the duration of fire exposure. This criterion ensures that premature structural collapse does not occur during the fire. Some codes allow a reduction factor to be applied to the specified loads for fire design. For example, the Eurocode gives an equation for determining a load reduction factor for fire design based on several factors, including percentage of permanent loads and type of principal variable load (Eurocode 2004). As an alternative to this equation the Eurocode allows the use of a reduction factor of 0.7.

4.3 Current Design Methods for Walls in Fire

This section summarizes the current methods allowed by different codes and design standards to design concrete walls to resist fire. Generally, engineers can satisfy fire safety requirements through any of three methods: choosing wall sections that satisfy the required fire rating based on charts and tables available in building codes, using a wall section that has been tested and approved for a certain fire rating by a certified testing facility, or determining the fire resistance of a wall section using “rational design”.

The simplest and most direct method available for engineers to design concrete walls for fire is to choose wall sections that satisfy the required fire rating based on charts and tables in building codes. Almost all charts and tables in building codes for the design of concrete walls for fire assume that the design is governed by the first criterion, temperature insulation. Based on this assumption, the CPCI Design Manual provides the chart shown in Figure 4 for determining the fire rating of concrete walls based on thickness and concrete type.

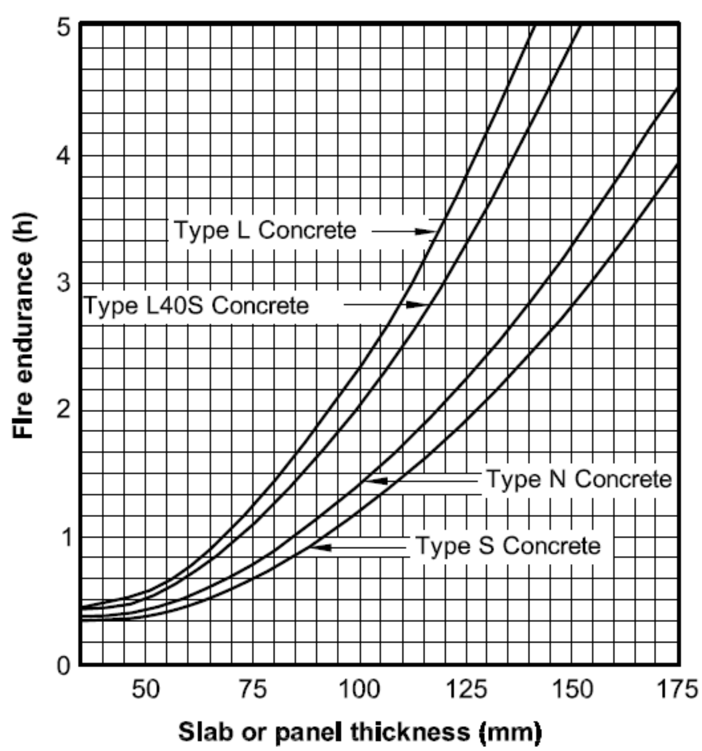


Figure 4: Chart for Determining Fire Resistance of Walls (CPCI Design Manual 2007)

ACI 216R-89 provides a chart almost identical to Fig. 4. Eurocode 2 provides a chart that specifies minimum thickness and reinforcement cover based on the required fire rating, whether the wall is exposed to fire on one or both sides, and a parameter that accounts for the value of the applied design load during fire as compared its value under normal conditions (Eurocode 2004).

A second straightforward method available to engineers to design concrete walls for fire is to use a wall assembly that has been tested and approved for a certain fire rating by an approved testing facility. For example, in Canada the NBC permits the use of wall sections that have been tested and approved by the Underwriters Laboratories of Canada (CPCI 2007). Problems with this method include the facts that there are few tested concrete wall assemblies and that testing new wall assemblies is both expensive and time-consuming.

The final method allowed by most codes for the design of concrete members is known as “rational design”. It is an analytical method for calculating the fire rating of a wall. As the second criterion for fire resistance, structural integrity, is difficult to evaluate analytically, it is generally assumed that this criterion is met provided the temperature insulation criterion is met (Eurocode 2007).

The Eurocode states that for all concrete structural members, including walls, “advanced calculation methods shall provide a realistic analysis of structures exposed to fire” and “shall be based on fundamental physical behaviour leading to a reliable approximation of the expected behaviour” (Eurocode 2004). Additional guidelines are given, such as what factors should be considered in the thermal and structural models that are used. The Eurocode also currently requires that any results from advanced calculation methods be verified through experimental testing. ACI 216R-89 assumes that the design of concrete walls for fire is governed only by the temperature insulation criterion, and thus bases the entire rationale for the design of concrete walls on thickness. No suggestions as to a rational design method for the fire design of concrete walls are given. The CPCI Design Manual also assumes that the design of concrete walls in fire is based only on thickness. However, it is stated that rational design methods may be used provided they are approved by the building authority having jurisdiction (CPCI 2007).

Although little information pertaining to the rational design of concrete walls for fire is currently given or referenced in building codes, it should be noted that building codes are moving more towards performance-based design. It can thus be expected that there will be more allowance for rational design in future building codes. For example, it is anticipated that the next edition of ASCE7, the American standard specifying minimum design loads on structures, will contain a section for fire loads. This section marks the first step in a move towards performance-based design.

5 Available Research on the Design of Concrete Wall during Fire

5.1 Experimental Research

Although experimental research does not provide engineers with an analytical method for designing concrete walls for fire, its value lies in validating both current and future analytical models and providing a general idea of what factors significantly influence the performance of concrete walls in fire.

The single most significant piece of experimental research available to engineers is an experimental program conducted by Crozier and Sanjayan (2000). Eighteen different walls with varying height-to-thickness ratios, reinforcement covers, concrete strengths, and concrete mixture proportions were tested. Eight of the walls were tested under combined eccentric axial and lateral loads to investigate the in-plane load capacity. The remaining ten walls were tested under lateral loads only to investigate the effects of spalling and thermal bowing. Two of these walls were tested while being supported along three edges to investigate the effect of flexural cracking on the spalling performance of concrete walls. Conclusions of the experimental program include: thermal bowing has a significant effect on the in-plane capacity of concrete walls, concrete strength has little effect on the fire performance of concrete walls, the level of in-plane load has a significant effect on the structural fire performance of concrete walls, and flexural cracking significantly reduces the effects of spalling in concrete walls exposed to fire.

Lee and Lee (2012) conducted an experimental investigation of the fire resistance of concrete walls exposed to fire from both sides. They tested eight walls while varying wall thickness, concrete strength, reinforcement ratio, level of axial load, and curing period. Results of their experimental program show that wall thickness and load level have a major effect on the performance of concrete walls in fire while concrete strength and reinforcement ratio have a minor effect.

Ta et al. (2011) tested four normal strength and six high strength concrete walls primarily for the purpose of comparing the performance of normal and high strength concrete walls. The primary observation of this experiment was that high strength wall suffered far more severely from spalling damage than normal strength concrete walls.

5.2 Analytical Methods

Several researchers have developed methods to model the performance of reinforced concrete walls during fire using finite element software. A finite element model by McGinnis et al. (2011) using the finite element software ABAQUS is being used to investigate the axial-load-moment-curvature-temperature behaviour of concrete walls exposed to fire. McGinnis et al. (2011) provided details about the finite element model and their initial experiments to validate it.

Zheng et al. (2011) have also developed a finite element model of concrete walls under fire using ABAQUS. Walls modeled in this research were subjected to both axial and lateral loads. A parametric study was performed to investigate the effects of axial load level, lateral load level, height-to-thickness ratio, wall thickness, concrete compressive strength, steel reinforcement yield strength, steel reinforcement ratio, and reinforcement cover. The results of this model are not compared to any experimental and/or analytical data, and thus the accuracy of the model cannot be validated. It is also worth noting that the paper claims that the capacity of concrete walls under fire exposure decreases with increasing concrete cover. This is contrary to results provided by several other researchers (Crozier and Sanjayan 2000).

Crozier and Sanjayan (1997) have presented a method for analyzing concrete walls in fire using the finite difference method. The program TASEF is used to calculate the temperature distribution throughout the different layers and temperature dependent properties for steel and concrete layers are calculated. An incremental solution using the finite difference method is applied to determine equilibrium between external loads and internal forces in the wall. This procedure is repeated until equilibrium cannot be maintained. A parametric study was performed to evaluate the importance of accurately modeling the ultimate concrete strain, the thermal strain, and the descending branch of the stress-strain curve. It is concluded that accurate prediction of the thermal strain is critical whereas modification of the ultimate strain or the slope of the descending branch has little effect on the capacity of the wall.

Several researchers have also presented analytical methods for analyzing concrete walls during fire that do not require finite difference or finite element models. One such method presented by Liu et al. (2012) analyzes a concrete wall during a fire using simple sectional analysis. The wall is divided into elements along its thickness and the temperature dependent properties of steel and concrete are calculated for each element. The method then assumes a certain strain profile and calculates the corresponding total strain in each element. The thermal, transient, and creep strains are then calculated for each element and the stress-related strain is then calculated by taking the difference between the total strain and the sum of the thermal, creep, and transient strains. Because the equations used to calculate transient and creep strains depend on the stress-related strains, an iterative procedure is required to obtain the final stress-related strain in each element. The stresses corresponding to the stress-related strains are then obtained. The deflection of the wall is then calculated and the entire procedure is repeated with the new deflected shape in order to account for the P-delta effects. The results of the model are only compared to one experimental test from research by the same authors and do not show good compatibility. Therefore, the validity of this model cannot be validated without further investigation. This model also does not provide engineers with a useful tool to evaluate the performance of concrete walls in fire as the method is not described in enough detail to be practically applied. A further drawback of this method is the iterative solution required to calculate the stress-related strains in the various elements.

Deam (2008) has presented another method for analyzing concrete walls in fire by integrating the beam equation over the height of the wall. This method utilizes an empirical equation from the New Zealand building code to calculate the temperature distribution and the Eurocode stress-strain curve for concrete under elevated temperatures. Walls are analyzed by using a method known as 5-point Lobatto curvature to integrate the beam equation over the height of the wall while accounting for the effect of elevated temperature by using temperature dependent properties. P-delta effects are accounted for by calculating the deflection of the wall and rerunning the analysis with the new deflected shape. The paper states that the results of the model apparently agree well with a finite element model but no comparison of results is given. Because of the complexity of the integration and interpolation used in this method, it is not suitable for practical engineering use. Also, the fact that transient creep is not accounted for in the model raises questions as to the accuracy of the model.

O'Meagher and Bennetts (1991) have presented a method for analyzing concrete walls in fire that is similar to that proposed by Liu et al. (2012). The model uses TASEF to calculate temperature distribution and then calculates temperature dependent properties for various layers in the wall. It then uses a sectional analysis method similar to that used by Liu et al. (2012) to calculate the stresses in different elements. Different cases were studied to determine what factors have a significant effect on the performance of the wall. It was found that P-delta effects have a significant impact on the performance whereas concrete tensile strength and creep effects have an insignificant effect. A parametric study was also performed to determine the effect of various parameters, including location of reinforcement, axial load level, slenderness ratio, effects of pre-stressing, amount of reinforcement, and the effects of end restraint. It was found that slenderness ratio, location of reinforcement, and axial load level had a significant effect on the wall capacity whereas the amount of reinforcement had little effect. The effects of pre-stressing and end restraint were also observed to have significant beneficial effects on the wall capacity. The model is not suitable for practical engineering use as only a general description of the methods used is given. Also, some pertinent details, such as how the transient creep strain is accounted for, are completely left out.

Lee and Lee (2012) have presented a method to determine the capacity of walls that are exposed to fire from both sides. The model is unique in two respects, first in that it considers fire exposure from both sides and second in that it attempts to account for the effects of spalling on the structural capacity of the wall. Spalling is accounted for by removing concrete layers in which the pore pressure, calculated as per the model suggested by Dwaikat and Kodur (2009), exceeds the concrete tensile strength. Any steel reinforcement that has been exposed by the spalling is ignored in the analysis. The accuracy of this model is questionable due to the disputes and questions surrounding accurate modelling of spalling as mentioned in section 2.2. Although equations are given to calculate the different strain components in concrete and steel and a general method is described, it is not clearly shown how the equations used are incorporated into the model. This again makes it difficult for engineers to use this model to perform structural analysis. Based on best fitting of the model results predicted, a simple linear equation depending only on wall thickness and axial load level is presented for calculating the capacity concrete walls. The equation is limited in that it does consider temperature insulation criterion and only applies for walls with a concrete cover of 20 mm, a reinforcement ratio of 0.0012, and fire exposure from both sides.

5.3 Research on the Occurrence and Effects of Spalling

Research on the occurrence and effects of spalling is numerous but with significant variation. The experimental tests conducted by Crozier and Sanjayan (2000) observed spalling in only three of eighteen specimens tested. Two of these specimens were restrained from deflection along three edges, thus preventing flexural cracking, and the third specimen was made of high-strength concrete. Guerrieri and Fragomeni (2010) tested four slender concrete walls to evaluate their spalling performance. Two specimens were tested under self-weight only and two specimens were tested with in-plane loading. Explosive spalling occurred in only one of the specimens tested with self-weight only. An experimental study by Ta et al. (2011) illustrated that that the effects of spalling on high-strength concrete walls is far more pronounced than in normal-strength concrete walls. The general conclusion of such observations is that spalling has a significant effect on high strength concrete walls and walls restrained from out-of-plane deflection and cracking, but little effect on normal strength walls that are unrestrained to out-of-plane deflection.

Numerous attempts have been made to create models that predict the pore pressure and the resulting spalling of concrete structures. These include attempts at modeling walls (Selih et. al. 1994; Abdel-Rahman and Ahmed 1996), and concrete members in general (Dwaikat and Kodur 2009). Although these models can be helpful in evaluating relative performance and determining what factors influence the spalling of concrete walls during fire, they cannot be used as to predict the definite spalling behaviour of walls as they only account for the effects of pore pressure on spalling performance and do not include the effects of thermally induced thermal stresses.

6 Assessment of Concrete Walls after Fire

Research in this area is limited to two experimental studies on the behaviour of shear walls after exposure to fire. Experimental research by Liu et al. (2010) shows that reinforced concrete shear walls exposed to fire suffer a loss in lateral load capacity, energy dissipation, and stiffness. It is also noted that an increase in reinforcement ratios can offset these effects due to the ability of steel to recover some of its strength after exposure to high temperatures. It is assumed that the post-fire axial performance of concrete walls would also be reduced due to fire exposure. Experimental research by Xiao et al. (2004) shows that the effect of fire exposure on high strength reinforced concrete walls is even more pronounced than the effect on normal strength walls.

7 Conclusion: Research Needs

As building codes move more towards performance-based design for fire, engineers need the tools necessary to efficiently and accurately evaluate the performance of concrete walls in fire. Two tools are required to accomplish this purpose: a simple method to evaluate the temperature distribution in a concrete wall during fire and a simple method to evaluate the capacity of concrete walls exposed to fire. Such tools will allow engineers to easily satisfy both the temperature insulation criterion and the structural adequacy criterion. In keeping with current practise, it might be reasonable to assume that the structural integrity criterion will be satisfied provided that the temperature insulation criterion is satisfied.

The methods available in current literature for evaluating the temperature distribution and capacity of concrete walls exposed to fire are impractical for one or more of the following reasons: they involve expensive and time-consuming finite element or finite difference methods, they do not adequately describe the required steps, equations, and methodology required to implement the model, or they do not account for certain pertinent factors, such as the effect of transient creep. A simple, accurate, and direct method for evaluating both the temperature distribution and the capacity of concrete walls in fire is needed.

Experimental studies show that the effects of spalling in walls exposed to fire are significant in high-strength concrete walls and generally insignificant in normal-strength concrete walls. Almost all current models for evaluating the capacity of normal-strength walls during fire assume that the effects of spalling are negligible. Additional investigations are required to validate this assumption. A methodology to account for the effects of spalling in the design of high-strength concrete walls is also needed.

Furthermore, a method for engineers to calculate the lateral, axial, and out-of-plane capacity of concrete walls after exposure to fire is needed. This will involve applying the known material properties of concrete and reinforcing steel after exposure to fire to analytical methods for evaluating the capacity of concrete walls. Experimental studies are also required to validate any proposed methods.

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