REINFORCED CONCRETE WALLS DURING FIRE

Investigation of the Out-of-Plane Flexural Capacity

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Abstract

Current building codes address the design of concrete walls for fire by specifying minimum thicknesses and concrete covers based on required fire ratings. As building codes move towards performance-based design for fire, it is important to provide engineers with tools to design concrete walls to resist fire. The out-of-plane flexural capacity of a wall is critical to resist loads associated with the hose stream during fire-fighting efforts, wind loads, and movements perpendicular to the wall longitudinal axis. In this paper, a parametric study is conducted to evaluate the effect of different parameters on the out-of-plane flexural capacity. A simplified sectional analysis method is utilized to sketch the moment-curvature diagrams of different walls. Results are examined to assess the effect of each of the considered parameters on the wall out-of-plane performance and capacity.

Keywords: reinforced concrete, walls, fire resistance, elevated temperature, structural behaviour, out-of-plane, flexural capacity

INTRODUCTION

Reinforced concrete walls form an integral part of the structure of many buildings. They resist gravity, in-plane, and out-of-plane loads and provide fire separation between different compartments within a building. Designing concrete walls to resist the effects of fire is critical for the performance of structures and the safety of building occupants and fire fighters. Fire affects the performance of concrete members by reducing the strength and stiffness properties of concrete and steel and introducing new strains in the concrete in the form of thermal strains and transient creep strains. Currently, engineers design concrete walls for fire by specifying minimum thickness and concrete cover from applicable standards and building codes. However, building codes are moving towards performance-based design for fire and as a result there is a need to provide engineers with a simple method to design concrete walls for fire. One of the critical loads to be considered in this design is the pressure applied by the hose stream during fire fighting efforts (CPCI 2007). As this load is applied in the out-of-plane direction, it is critical to establish the out-of-plane capacity of concrete walls during fire. This paper addresses this need by utilizing a simplified sectional analysis method developed by El-Fitiany and Youssef (2009) to perform a parametric study and sketch moment-curvature diagrams for various walls. The effect of several different parameters, including axial load level, fire orientation, fire duration, concrete cover, and wall thickness, on the performance and capacity of the wall is noted and discussed.

1 MODEL DESCRIPTION

A detailed description of the method used to model concrete walls in this paper has been presented by El-Fitiany and Youssef (2009). In summary, the model uses the well-known sectional analysis method to predict the flexural and axial behaviour of reinforced concrete sections during exposure to elevated temperatures. The finite difference method is utilized to predict the temperature distribution throughout the section as a function of time. The section is divided into layers and temperature dependent properties of concrete and steel are then calculated for each layer. The stress-strain relationship for concrete and steel at elevated temperatures proposed by Youssef and Moftah (2007) is adopted in the model. This relationship accounts for the effects of transient creep by shifting the value of the strain at peak stress by the transient creep strain.

The average temperature of each layer is used to calculate the induced thermal strains. As the distribution of thermal strains is not linear throughout the section, an equivalent linear strain is evaluated such that the axial forces and bending moments in the concrete and steel are in self equilibrium. For each layer, the difference between the evaluated linear strain and the actual thermal strain represents the induced mechanical strain required to retain the linearity of the section. This procedure ensures that plane sections remain plane, which is still the case at elevated temperatures (El-Fitiany and Youssef 2009). These induced mechanical strains are included as initial strains in the model. Once the distribution of the thermal strains is known, the mechanical strain in each layer can be calculated by subtracting the thermal strain from the total strain. Sectional analysis can then be performed using temperature dependent properties and the stress-strain relationship mentioned above. The advantages of this model are its simplicity and efficiency as compared to finite element models.

2 MODEL VALIDATION

Although this sectional analysis model has been previously validated (El-Fitiany and Youssef 2009; El-Fitiany and Youssef 2008), these validations have only considered column and beam specimens. Additional validation of the model for the case of walls was performed in this paper. The wall specimen tested by Crozier and Sanjayan (2000) was 150 mm thick and 3.2 m long, and was exposed to fire on its tension side. Concrete strength was 52 MPa. Reinforcement ratio of 0.25% was arranged in two layers and was placed considering a clear cover of 30 mm. The specimen was placed on its side and simply supported at each end, and was thus laterally loaded by its own self-weight in addition to an applied eccentric axial load. Results were presented in terms of mid-span deflection of the wall for up to one hour of fire exposure. The specimen was modelled using the method described in section 1, and the resulting curvature at various temperatures was used to predict the mid-span deflection of the wall. The good agreement between the predicted deflection and the measured deflection, Figure 1, provides further validation for the model, specifically in the case of walls.

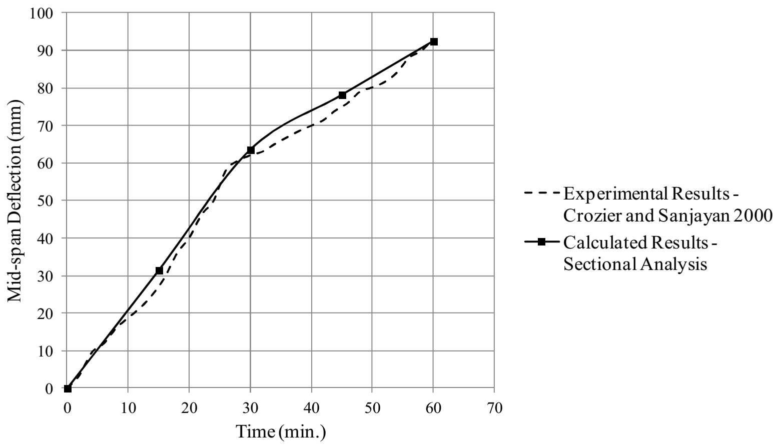

Fig. 1 Model Validation

3 PARAMETRIC STUDY

A parametric study was performed to investigate the effects of various parameters on the out-of-plane flexural capacity of concrete walls. A summary of the parameters included in the study, the range over which the parameters were considered, and the percentage effect on the capacity is presented in Tables 1 to 3. Because the axial load level was found to have a significant influence, results are presented for two separate axial load levels, 0 and 0.4. An axial load level of 0 represents the pure flexural capacity of walls, and is valid as well for standard slabs. An axial load level of 0.4 corresponds to the approximate balance point on the interaction diagram for the wall. The results are presented for walls exposed to fire from their tension side, their compression side, or both sides. The tables show the percentages for the maximum change in capacity caused by varying each parameter within the range shown.

Tab. 1 Results - Fire on Tension Side of Wall

Parameter	Range	Effect on Flexural Capacity (axial load level = 0)	Effect on Flexural Capacity (axial load level = 0.4)
Fire Duration (hrs)	0-2	49.4%	79.7%
Concrete Clear Cover (mm)	20-60	65.6%	102.6%
Wall Thickness (mm)	210-400	32.8%	27.7%

Tab. 2 Results - Fire on Compression Side of Wall

Parameter	Range	Effect on Flexural Capacity (axial load level = 0)	Effect on Flexural Capacity (axial load level = 0.4)
Fire Duration (hrs)	0-2	73.5%	53.5%
Concrete Clear Cover (mm)	20-60	109.7%	108.4%
Wall Thickness (mm)	210-400	26.5%	22.6%

Tab. 3 Results - Fire on Both Sides of Wall

Parameter	Range	Effect on Flexural Capacity (axial load level = 0)	Effect on Flexural Capacity (axial load level = 0.4)
Fire Duration (hrs)	0-2	39.8%	46.9%
Concrete Clear Cover (mm)	20-60	69.2%	103.3%
Wall Thickness (mm)	210-400	28.2%	22.1%

Concrete and steel strength and reinforcement ratio were not included in the parametric study as previous studies had shown that these parameters have little effect on the capacity of a concrete wall (Crozier and Sanjayan 2000; O'Meagher and Bennetts 1991; Lee and Lee 2012). The walls were analyzed as sections only, and thus height-to-thickness ratios and buckling effects were not considered. All walls had a reinforcement ratio of 0.15%, concrete strength of 30 MPa, steel yield strength of 400 MPa, and were composed of siliceous type concrete. The reinforcement ratio of 0.15% corresponds to the minimum amount of reinforcement required by the Canadian concrete standard (CSA 2004). The effect of each of the different parameters is discussed in the following sections.

3.1 Axial load level

The presence of axial load had a significant effect on the moment capacity, increasing the capacity by up to 975%. This is due to the low reinforcement ratio in the walls, which results in lower moment capacity for walls with no axial load. The presence of a compressive axial load reduces or entirely eliminates any tension force in the wall. Results for a 210 mm thick concrete wall that was exposed to fire for one hour on its tension side and had a concrete cover of 20 mm are shown in Figure 2. As illustrated in the figure the presence of axial load had a large beneficial impact on the capacity of the wall. The figure also illustrates that an axial load level of 0.4 corresponds to the approximate balance point on the interaction diagram.

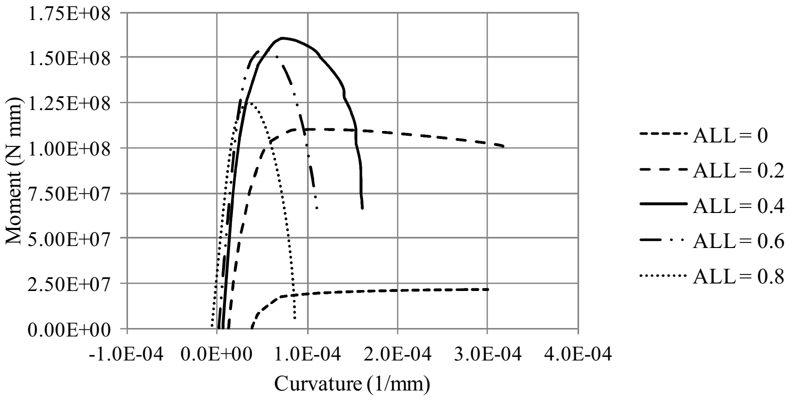

Fig. 2 Effect of Axial Load Level

The effects of higher axial load illustrated in Figure 2 were similar for all other fire orientations, fire durations, concrete covers, and wall thicknesses. As illustrated in Tables 1 and 3, the presence of axial load also had a significant impact on the effectiveness of concrete cover for walls exposed to fire on the tension side or from both sides. The flexural capacity of such walls with no axial load was significantly affected by increased cover, whereas the capacity of walls with higher levels of axial load was marginally affected by increased cover.

3.2 Fire Orientation

Changing the fire exposure from one to two sides was found to decrease the capacity of the wall up to 62% for walls exposed to fire on the tension side and up to 48% for walls exposed to fire from the compression side. As illustrated in Fig. 3, for the case of fire on the compression side of the wall the effect of two-sided fire exposure was markedly reduced by either increasing the axial load level or increasing the amount of concrete cover. All specimens shown in Figure 3 had a thickness of 210 mm, were exposed to fire for one hour, and in cases of one-sided fire exposure were exposed to fire on the compression side.

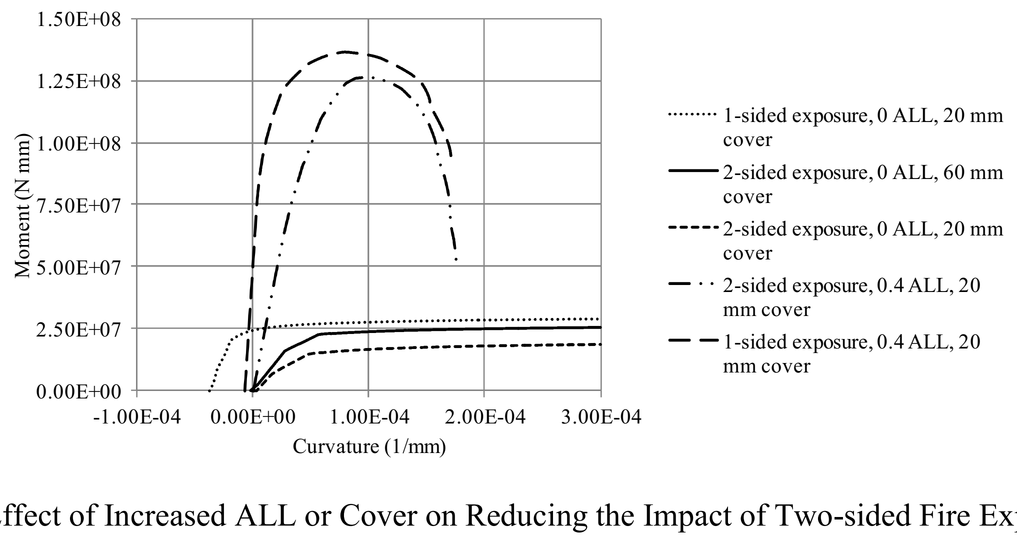

Fig. 3 Effect of Increased ALL or Cover on Reducing the Impact of Two-sided Fire Exposure

For cases of 20 mm cover and no axial load, walls exposed to fire on the tension side were approximately 70% weaker than the same walls exposed to fire on the compression side. Walls with 60 mm cover and no axial load had approximately the same capacity whether fire was applied to the tension or compression side. Walls with an axial load level of 0.4 performed approximately 20% better when exposed to fire on the tension side as opposed to the compression side. This is due to the fact that such walls failed in compression, with the compressive strength further reduced due to fire exposure.

3.3 Fire duration

As illustrated in Tables 1 and 2, increasing the fire duration from 0 to 2 hours in walls exposed to fire from either the tension or the compression side significantly lowered the moment capacity. As is expected and as illustrated in Figure 4, the effect of increasing the fire duration was slightly more pronounced in the cases of walls exposed to fire from both sides, up to a maximum of 40%. All walls shown in Figure 4 had a thickness of 210 mm, cover of 20 mm, and were exposed to fire from both sides.

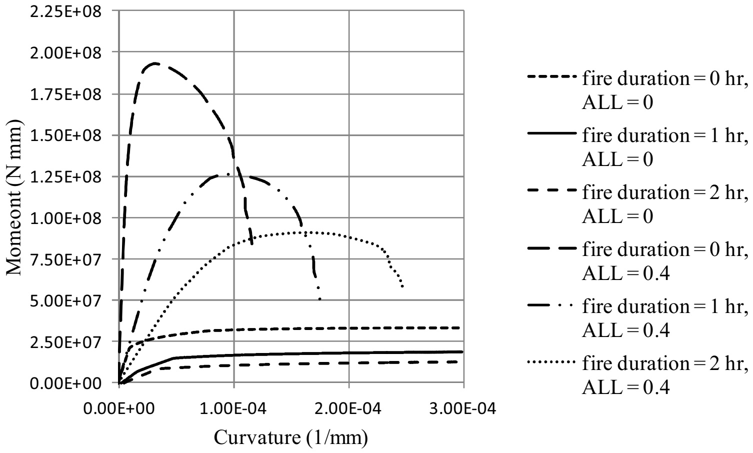

Fig. 4 Effect of Fire Duration on Walls Exposed to Fire on Both Sides

3.4 Concrete cover

As illustrated in Tables 1 and 3, decreasing the concrete cover from 60 mm to 20 mm decreased the capacity of the walls by a maximum of 65-70%. This is because an increased concrete cover provides better temperature insulation for the reinforcement, thus lowering the impact of the fire on the strength of the reinforcement. This reduction of capacity was only representative of walls with both a low axial load and exposure to fire on the tension side. As illustrated in Figure 5, the effect of increasing the concrete cover for cases of an axial load level equal to 0.4 was negligible, and in the majority of cases slightly decreased the capacity. All walls shown in Figure 5 had a thickness of 210 mm, were exposed to fire on the tension side only, and had an axial load level equal to 0.4.

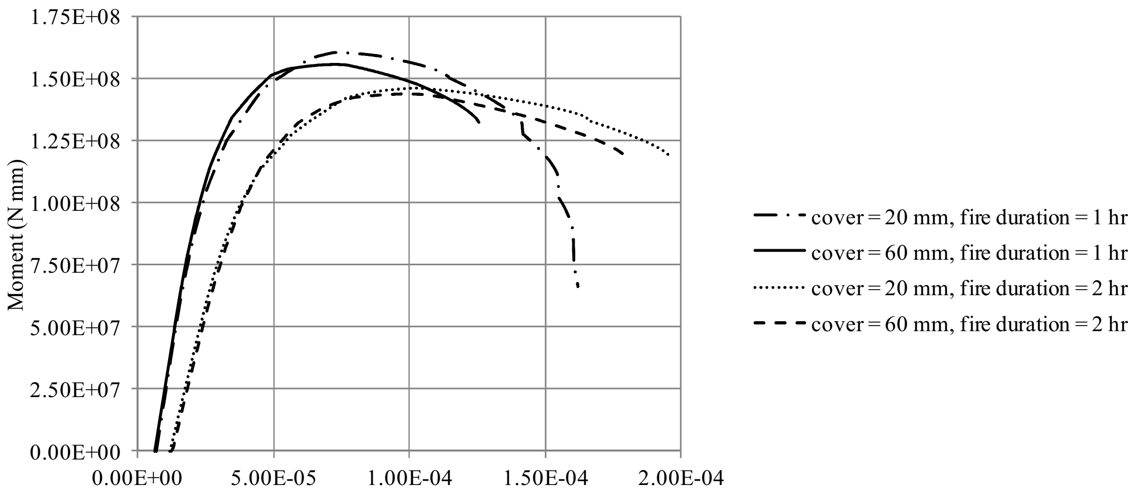

Fig. 5 Negligible Effect of Cover with a Higher Axial Load Level

3.5 Wall thickness

The results show that wall thickness is one of the most important parameters to be considered in the design of concrete walls for fire. As illustrated in Tables 1-3, the effect of varying the wall thickness from 400 mm to 210 mm was approximately uniform throughout all sections considered, ranging from 22% to 35%. In general the effect of the wall thickness on the capacity was approximately 5% greater for cases with an axial load level of 0 as opposed to cases with an axial load level equal to 0.4.

4 CONCLUSION

The results of this research show that all five parameters considered have a significant impact on the design of concrete walls for fire. Increasing the level of axial load up to a level of 0.4 significantly increased the out-of-plane flexural capacity of all walls considered. The significant effect of axial load level illustrates the importance of considering different load cases during the design of concrete walls for fire, as the case of minimum axial load will likely govern the out-of-plane capacity. Another reason to consider different axial load cases is the fact the failure mode of the wall is dependent on the axial load level.

Changing the fire exposure from one to two sides significantly reduced the capacity of many of the walls considered. In the case of fire on the tension side of the wall, this effect was less significant in walls with a thickness of 400 mm. In the case of fire on the compression side of the wall, this effect was less significant in walls with a higher axial load level or increased concrete cover. The varying effects of fire orientation illustrate the importance of considering all possible fire loading scenarios in the design of concrete walls.

The results show that concrete cover is a significant parameter only in cases where the tension side of the wall is exposed to fire and there is a low amount of axial load. In cases where these requirements are not met an increased amount of concrete cover was either negligible or slightly decreased the capacity of the wall.

Finally, the results show that wall thickness is one of the most important parameters to be considered. The beneficial effects of increased wall thickness were approximately uniform for all cases considered.

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