Moment-Curvature Relationship of Concrete Columns Exposed to Fire from Two, Three, and Four Sides

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Abstract

Designing structures so they have adequate structural integrity in the event of a fire is extremely important. Therefore, it is important to facilitate achieving the optimal designs, which achieve fire safety while allowing for innovative solutions. Such designs are expected to follow the performance-based design criteria, which replaced the prescriptive-based design criteria in several design standards. Engineers are in dire need for tools that allow utilization of this design approach. This research addresses this need. Simplified tools that evaluate the effect of the number of column surfaces exposed to fire on its structural behavior have been examined. A column exposed to fire on its tension and compression sides was found to have lower capacity than a column exposed to fire on one of these surfaces. Also, a column exposed to fire only on the tension side will have a lower capacity than a column exposed to fire only on the compression side..

Keywords: Concrete; Column; Elevated Temperatures; Moment-curvature; Fire resistance; Fire performance

Introduction

It is important to understand the effect of fire on reinforced concrete structures to ensure they are designed with adequate safety. Buildings are typically separated into compartments to limit the spread of fire, however, human intervention by opening doors or windows during evacuation can cause a fire to spread due to the increase in oxygen supply. Therefore, it is crucial to ensure that buildings will retain enough structural integrity for occupants to exit the building safely and provide time for emergency response teams to extinguish the fire. Design codes are currently using prescriptive methods for designing reinforced concrete structures, which involve specifying minimum thicknesses and concrete cover for specific fire ratings. The safety level provided by these methods at the structure level is unknown. Additionally, these methods limit implementing innovative solutions and using new materials. To address these issues, design codes are starting to switch to performance-based methods, which utilize realistic fire scenarios. In this paper, the effect of fire on the moment curvature relationships of a square concrete column will be explored when the column is exposed to fire from two, three and four faces.

Literature Review

As many codes are moving from prescriptive-based methods, that just meet specific criteria, towards performance-based criteria, that take into consideration realistic fire scenarios, it is important to simplify this process to ensure the most efficient design process. El-Fitiany (2013) proposed a set of simplified tools for performance-based design of reinforced concrete structures exposed to fire. These tools included a simple excel spreadsheet which can predict the axial capacity, the bending moment, or the interaction response of a column subjected to fire from any direction.

When reinforced concrete structures are exposed to fire, it causes the mechanical properties of both steel and concrete to decrease significantly. Once the fire is extinguished, they will start increasing towards their original values (Youssef et al. 2008). Youssef et al. (2008) studied the flexural behaviour of unreinforced and lightly reinforced siliceous concrete slabs after being exposed to high temperatures and presented models to predict concrete and steel mechanical properties during and after fire exposure. Concrete properties affected by fire include concrete compressive and tensile strength, concrete compressive strain, and bond strength of reinforcing bars.

Finite element methods have proven to be good tools for predicting the fire behaviour of concrete, however they do have limitations such as the long running time. El-Fitiany and Youssef (2009) introduced a simple method for predicting the flexural and axial behaviour of reinforced concrete sections. The method is based on the finite difference method to estimate the temperature distribution within a concrete section, and then a modified version of the sectional analysis approach is utilized to predict the axial and flexural behaviour. The simplified method proposed by El-Fitiany and . The sectional analysis approach had to be modified in order to account for the elevated temperatures. The analysis involves dividing the section into horizontal fibers to estimate the flexural and axial capacity of a section exposed to elevated temperatures. An average weighted temperature is assigned to each fiber.

Estimating the flexural capacity of reinforced concrete sections that are exposed to fire is complex. The mechanical properties of both steel and concrete deteriorate and this is accompanied by the generation of thermal and transient strains. El-Fitiany and Youssef (2011) presented simple equations to calculate the stress-block parameters, which can be utilized to accurately estimate the flexural capacity of simply supported and continuous beams exposed to fire temperatures. They conducted a parametric study where the stress and strain distributions at failure were predicted and the actual distributions were approximated to equivalent stress-blocks by using a multiple regression analysis.

Reinforced concrete structures must be designed for specific fire ratings, however, the fire resistance of reinforced concrete structures that are subject to damage from seismic activity is not considered during design. Earthquakes can lead to damage in reinforced concrete structures and this damage can affect the fire resistance of concrete and as fire after earthquakes is a real possibility, especially in urban areas, it is important to take this into consideration when designing concrete structures. The reduced fire resistance of these structures can cause the building to collapse much sooner than anticipated and the delays of emergency response teams during earthquakes can make this a catastrophic combination.

Objectives

The objective of this report is to examine the effects of fire on reinforced concrete columns exposed to fire on 2 parallel sides, 2 adjacent sides, 3 sides, and 4 sides.

Validation

As previously mentioned, El-Fitiany (2013) developed tools to predict the axial capacity, bending moment and interaction response for columns exposed to fire. The tools were tested for columns exposed to fire on four sides and the results are shown in figures 1 to 3. The graphs from El-Fitiany (2013) were plotted by the author of this paper using a web digitizer. The specimen used to validate the axial behavior was a concrete column with section dimensions of 305 mm by 305 mm. The specimen contained siliceous aggregate and four 25 mm steel bars. The compressive strength of the concrete was 36.1 MPa and the yield strength of the steel bars was 443.7 MPa. This specimen was exposed to a standard ASTM-E119 fire on four sides. The specimen used to validate the interaction diagram response was 600 mm by 600 mm and reinforced with twenty-four 20 mm steel bars. This specimen also had siliceous aggregate and the concrete compressive strength was 40 MPa while the yield strength of the reinforcing bars was 430 MPa. This specimen was exposed to an ISO 834 fire on four sides. The obtained responses are almost identical to the results by El-Fitiany (2013). The slight differences could be due assumptions related to the unknown input values. Nonetheless, this shows that the author was able to utilize the tools developed by El-Fitiany (2013) to predict the axial capacity, bending moment, and interaction responses of a concrete column exposed to elevated temperatures. The figures below show that the longer a column is exposed to fire, the weaker it is.

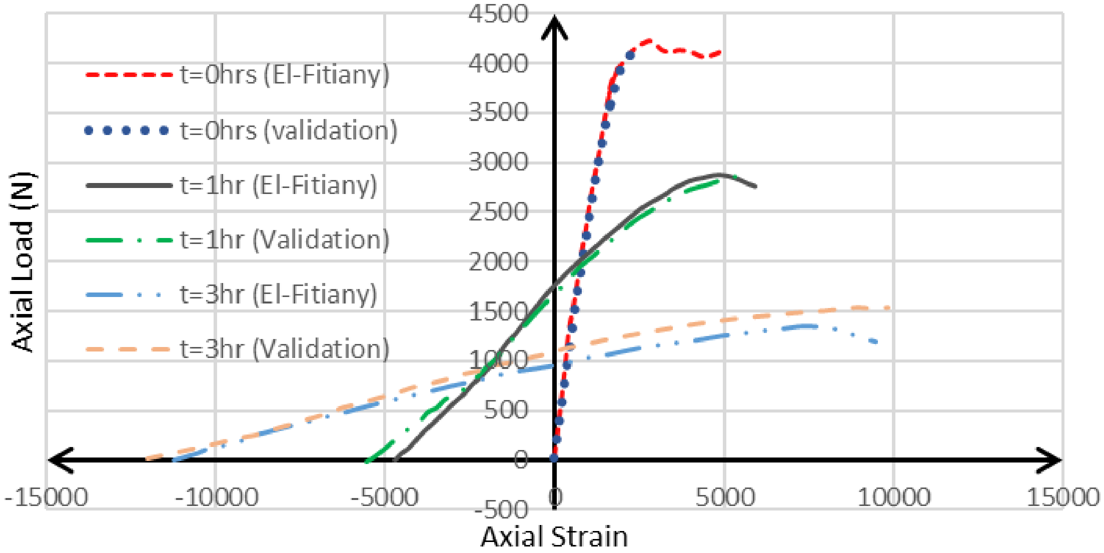

Figure 1: Axial Load-Axial Strain Behavior

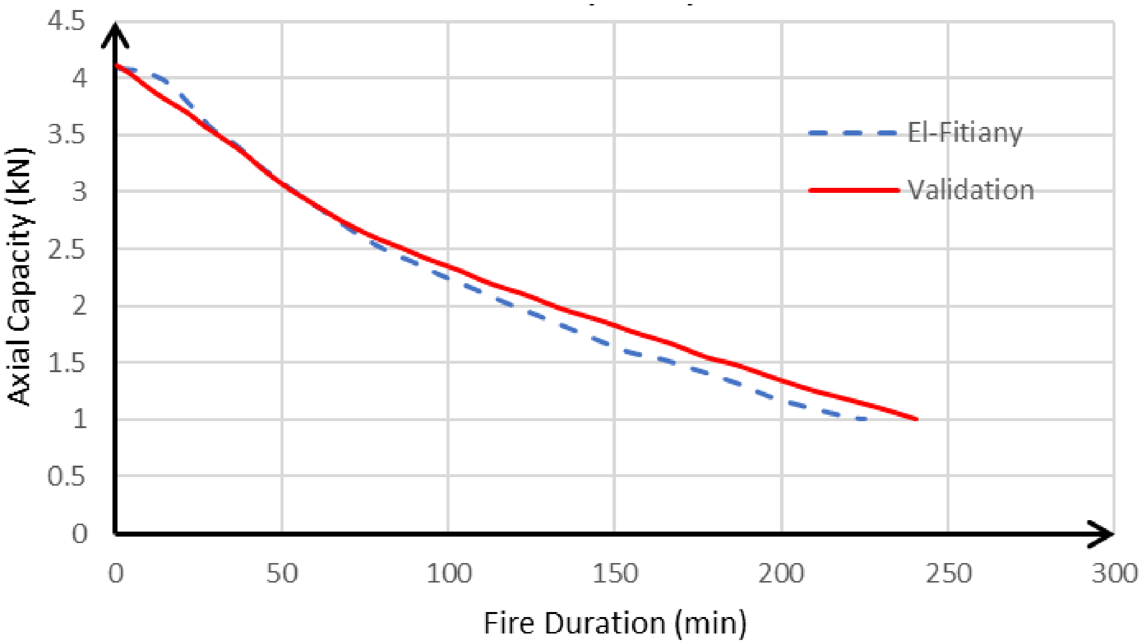

Figure 2: Variation of axial capacity with time

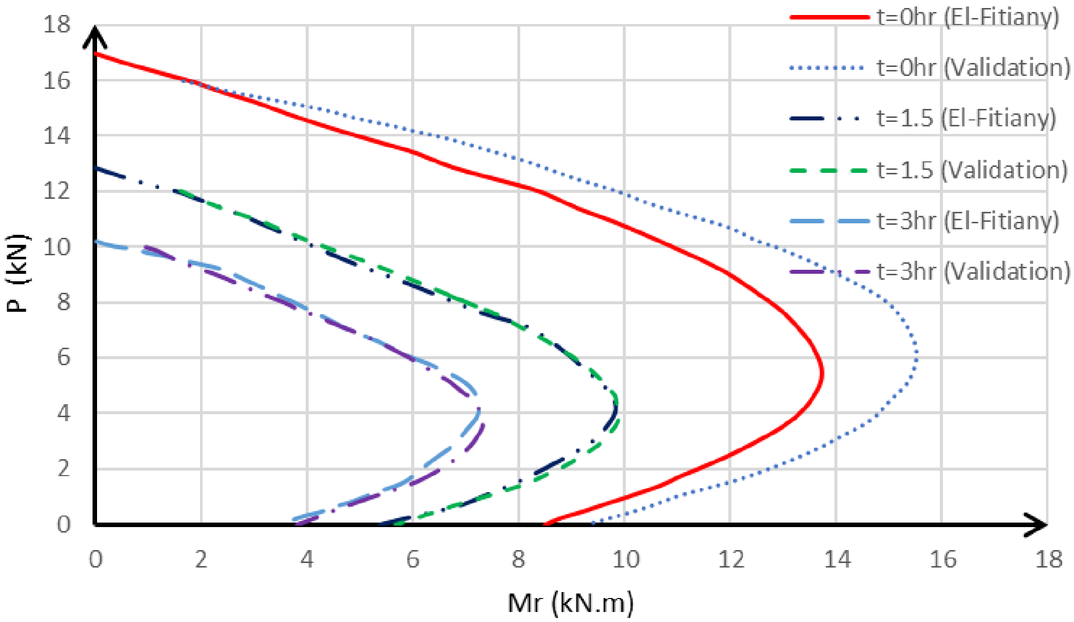

Figure 3: Interaction diagrams of a fire-exposed column

Case Study

In this section, the tools developed by El-Fitiany (2013) are used for columns exposed to fire from 3 sides and columns exposed to fire from 2 sides (with fire on parallel sides and adjacent sides). The moment-curvature relationships for each of these cases are plotted and the values for initial curvature, yield curvature, ultimate curvature, failure curvature, yield moment, ultimate moment, and failure moment are tabulated. These values and graphs are compared to the results from the column that was exposed to fire from 4 sides and to each other. The purpose of these comparisons is to understand the performance of concrete columns under different fire scenarios.

The column has a span of 4 meters and dimensions of 500 mm by 500 mm. It has an area of steel of 5000 mm^2 with 8 bars spread equally over the top and bottom sides and a concrete cover of 50 mm. The concrete compressive strength is 40 MPa, the yield strength of steel is 400 MPa, and the column is exposed to an ASTM-E199 fire for one hour (Youssef et al. 2008).

For the case of the column exposed to fire from 3 sides, two different scenarios will be examined. These cases include the column exposed to fire from the top, bottom, and right side and the column exposed to fire from the right, left, and top side. These two cases may produce slightly different results because when both the top and bottom side of the column are exposed to fire, the column is symmetric about the bending axis, and when only one of the sides is exposed to fire it is unsymmetric.

The case of the column exposed to fire from 2 sides also has different scenarios that will be examined for the parallel and adjacent cases. For the column exposed to fire from 2 parallel directions, these two parallel sides can either be the top and the bottom sides of the column or the right and the left sides of the column. It is important to include both of these cases because the top of the column is the compression side and the bottom is the tension side so it is important to see the difference in the capacities if fire is on the compression and tension side compared to when fire is exposed to neither of these sides. The column exposed to fire from 2 adjacent sides also has different scenarios and these include a column exposed to fire from the left side and the bottom side and a column exposed to fire from the left side and the top side. These should also produce different results because in one scenario fire will be exposed to the tension but not the compression side and in the other scenario fire will be exposed to the compression but not the tension side.

The moment-curvature relationships for the column exposed to fire from 4 sides, 3 sides, 2 parallel sides, and 2 adjacent sides can be seen in Figure 4 and the significant values can be seen in Table 1. The moment-curvature relationships for 2 adjacent sides, 2 parallel sides, and 3 sides compared to 4 sides individually can be seen in figures 5 to 7.

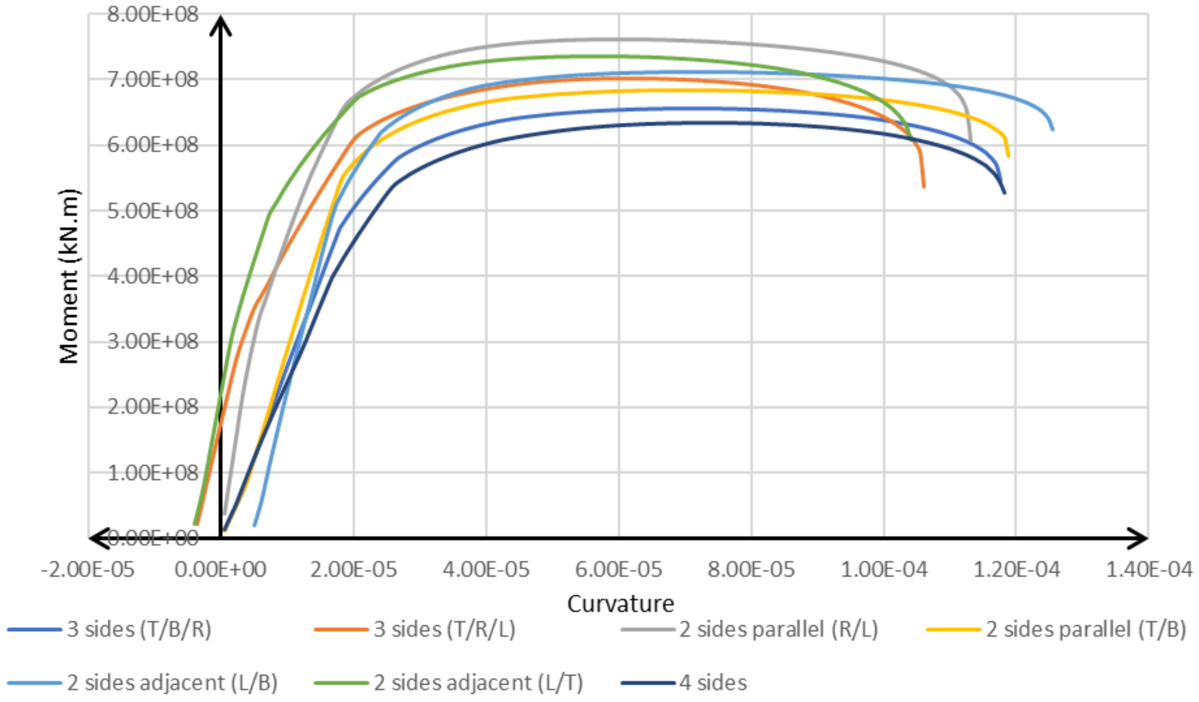

Figure 4: Moment-Curvature Diagrams for Different Cases of Fire Exposure

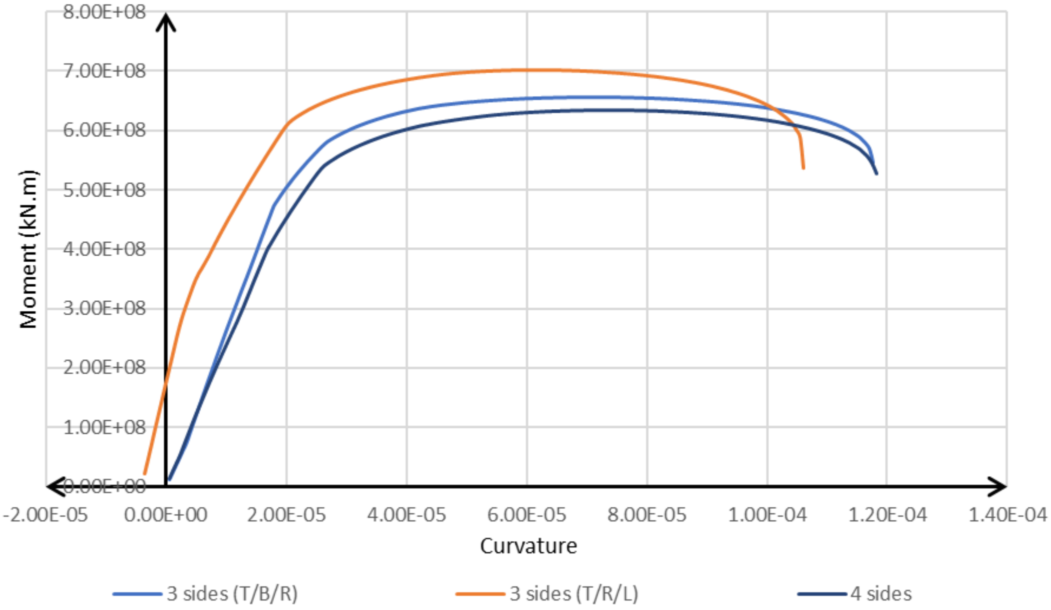

Figure 5: Moment-Curvature Diagrams for a Column Exposed to Fire on 3 sides

From figure 5, for columns exposed to fire from 3 sides, the column that was exposed to fire on the top, right, and left side has the highest ultimate moment value. However, it is the only case with an initial curvature due to its asymmetry and it fails at a smaller curvature value than both the column exposed to fire on the top, bottom, and right side and the column that was exposed to fire on all 4 sides. The column exposed to fire on the top, right, and left sides fails at the highest moment value.

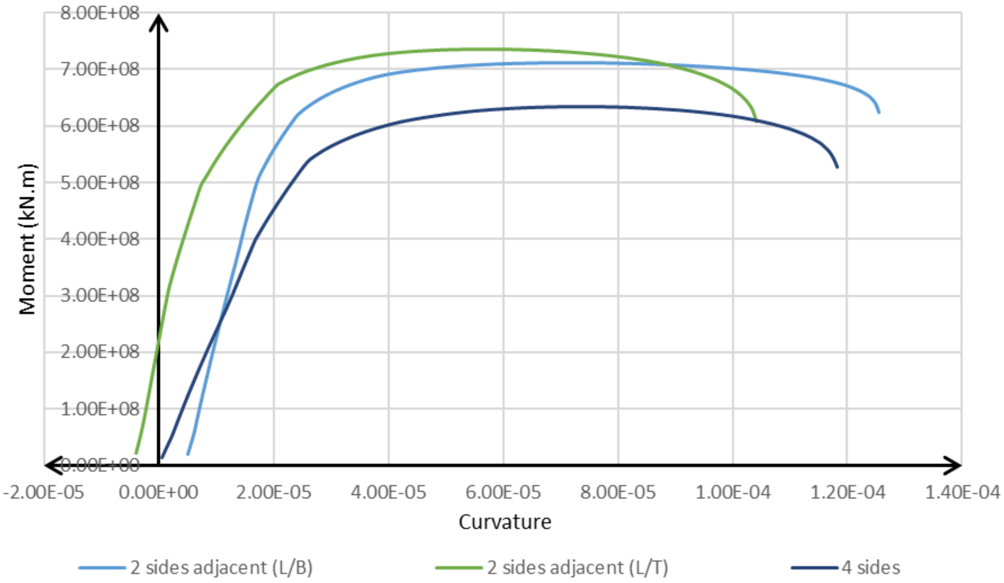

Figure 6: Moment-Curvature Diagrams for a Column Exposed to Fire on 2 Adjacent Sides

From figure 6, the column exposed to fire on the left and top side has the highest ultimate moment. However, it fails at a much smaller curvature value than the column exposed to fire on the left and bottom side as well as the column exposed to fire on all 4 sides. The column exposed to fire on 4 sides fails at the lowest moment value, however the column exposed to fire on the left and top side fails at the lowest curvature value. Both cases of columns exposed to fire on 2 adjacent sides have initial curvature values because both of these cases are unsymmetric about the bending axis.

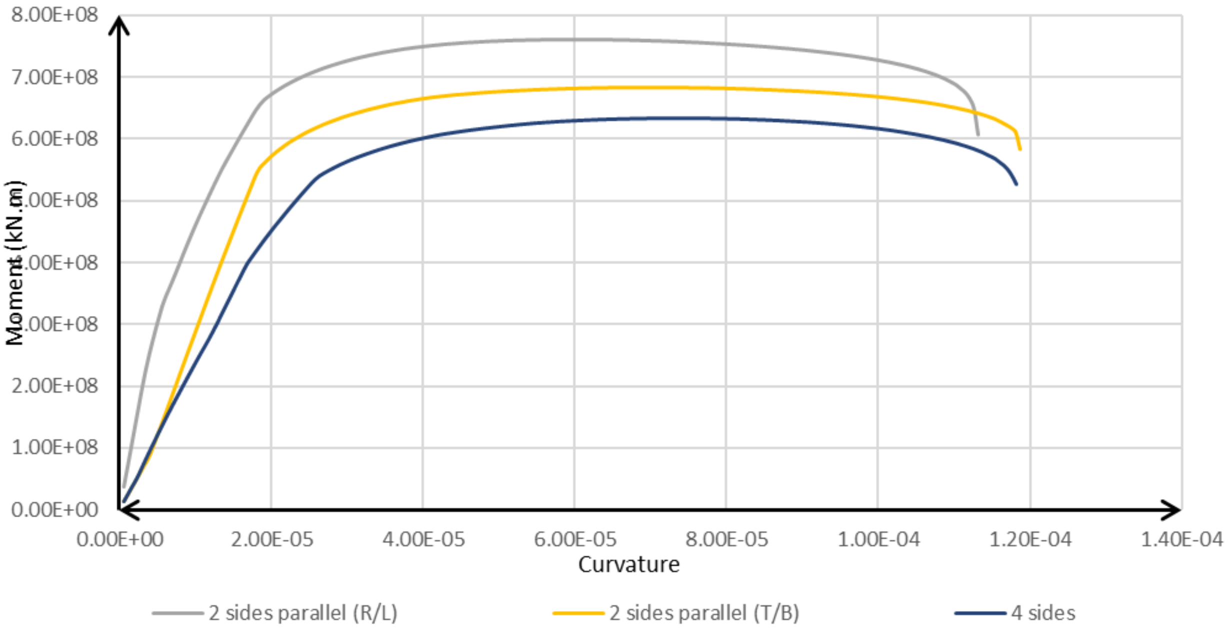

Figure 7: Moment-Curvature Diagrams for a Column Exposed to Fire on 2 Parallel Sides

From Figure 7, the column exposed to fire from the right and left sides has the highest ultimate and failure moment values whereas the column exposed to fire from the top and bottom sides has the highest failure curvature value. None of the cases shown in figure 7 have initial curvature values and this is because they are all symmetric about the bending axis.

Table 1: Moment and Curvature Values for Different Cases of Fire Exposure

Value	4 sides	3 sides (T/B/R)	3 sides (T/R/L)	2 sides parallel (T/B)	2 sides parallel (L/R)	2 sides adjacent (L/B)	2 sides adjacent (L/T)
$\Phi_{initial}$	0	0	-3.6×10^{-6}	0	0	5.12×10^{-6}	-3.97×10^{-6}
Φ_y	2.9×10^{-5}	2.5×10^{-5}	2.05×10^{-5}	1.4×10^{-5}	1.8×10^{-5}	2.5×10^{-5}	1.5×10^{-5}
Φ_{ult}	6.78×10^{-5}	7.34×10^{-5}	6.53×10^{-5}	7.51×10^{-5}	6.38×10^{-5}	7.57×10^{-5}	6.15×10^{-5}
$\Phi_{failure}$	1.15×10^{-4}	1.18×10^{-4}	1.06×10^{-4}	1.19×10^{-4}	1.13×10^{-4}	1.26×10^{-4}	1.04×10^{-4}
M_y	5.7×10^{8}	5.7×10^{8}	6.1×10^{8}	6×10^{8}	6.5×10^{8}	6.2×10^{8}	6×10^{8}
M_{ult}	6.33×10^{8}	6.57×10^{8}	7.01×10^{8}	6.84×10^{8}	7.62×10^{8}	7.13×10^{8}	7.36×10^{8}
$M_{failure}$	5.3×10^{8}	5.46×10^{8}	5.36×10^{8}	5.84×10^{8}	6.08×10^{8}	6.25×10^{8}	6.08×10^{8}

To obtain the yield moment and yield curvature values in this table the Park's Method was used (Park, 1988). This method starts with drawing a horizontal line from the peak of the curve, a line from the origin is then drawn so it intersects at a moment value that is 75% of the maximum moment and a vertical line is drawn at the intersection of these two lines to get the yield curvature (Park, 1988). An example of the Park's Method can be seen in Figure 8. The yield moment can be found from the data once the yield curvature is known. The initial curvature values were taken as the first value in the curvature column of the data. The failure curvature and failure moments were taken as the last values in their respective columns and the ultimate values were found using the MAX() function in excel to find the maximum moment values and taking the corresponding curvature values.

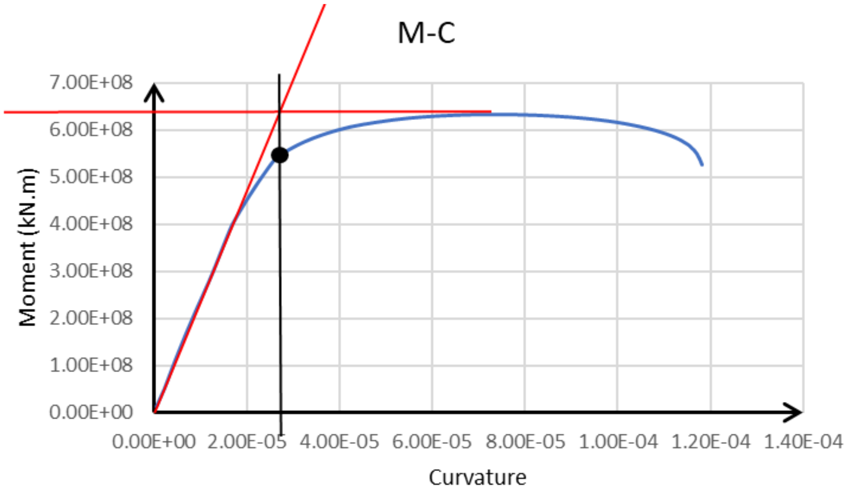

Figure 8: Park's Method for Determining the Yield Curvature

As shown in the table, some cases of fire exposure have an initial curvature while others do not. This is due to the symmetry of the fire about the bending axis. Unsymmetric thermal expansion about the bending axis will cause an initial curvature in the column. Any case with fire on the top and bottom sides will be symmetric about the bending axis and will therefore have no initial curvature. This can be seen in the table as the cases with fire on 4 sides, 3 sides with fire on the top, bottom, and right side, and both cases of fire on parallel sides have initial curvatures of zero.

Looking at Figure 7 and Table 1, it can be seen that a column exposed to fire from 4 sides fails at the lowest moment and curvature values and the column exposed to fire from 2 adjacent sides, the left and the bottom, fails at the highest moment and curvature values. The column exposed to fire from 4 sides also has the lowest ultimate moment and curvature values, however the column exposed to fire from 2 parallel sides, the right and the left, has the highest values. The top of the column is in compression while the bottom side of the column is in tension so when the fire is only on the right and left sides, there is no fire on the compression and tensions sides and therefore it is reasonable that the column exposed to fire from only the right and left sides has the highest ultimate moment value.

Using Figure 7 to compare the columns exposed to fire on both the top and bottom sides to the columns that are not exposed to fire on both the top and bottom, it shows that the columns with fire on both the top and bottom are generally weaker than when the fire is exposed to one or neither of these sides. The case with the lowest moment-curvature values is the column with fire on four sides. For the columns that were exposed to fire on three sides, the column exposed to fire on the top, bottom, and right side has lower moment-curvature values than the column exposed to fire on the top, right, and left sides. For the moment-curvature relationships for columns exposed to fire on parallel sides, the column exposed to fire on the right and left sides only has the highest ultimate moment and curvature values compared to any of the other cases, however the column exposed to fire on the top and bottom sides only has one of the lowest values, the only cases with smaller moment-curvature relationships are the column exposed to fire on the top, bottom, and right sides and the column that was exposed to fire on all four sides. Therefore, having fire on the compression and tension sides has significant weakening impacts on the moment-curvature relationships. Comparing the columns that were exposed to fire on two adjacent sides, the column exposed to fire on the left and the top sides has a higher moment-curvature relationship than the column that was exposed to fire on the left and bottom sides. Given that the top of the column is the compression side and the bottom is the tension side, this means that if fire is exposed to the tension side, it will have more of an impact and make the column weaker than if the fire was exposed to the compression side. As concrete is stronger in compression and relatively weak in tension, it is reasonable that the compression side will have higher ultimate moment values.

Summary and Conclusions

The effects of fire on concrete are important to understand for designing concrete structures, however it is still not a widely known topic. Prescriptive-based methods are traditionally used to design concrete structures which involve choosing floor and wall assemblies to meet specific criteria. These methods do not take into account realistic fire scenarios so new methods of designing reinforced concrete structures are needed to ensure the optimal design of these structures. This is why many codes are switching to performance-based design of concrete which takes into consideration all the factors affecting the performance of concrete structures exposed to fire and can evaluate the performance under realistic fire scenarios. Due to the increasing use of performance-based methods, it is important to simplify them as much as possible which is why El-Fitiany (2013) proposed simplified tools for performance-based design of concrete.

El-Fitiany (2013) created an excel spreadsheet that allows the section properties, concrete properties, steel properties, fire type and other properties to be inputted and then a program is run that can determine the stress-strain response, the bending moment response, and the interaction response. This program has been used for a column that was exposed to fire on all 4 sides and the results were recreated in this paper. The software was then used to examine the effects on the moment-curvature relationship of the same column that is exposed to fire on 3 sides, 2 parallel sides, and 2 adjacent sides. The results are then compared with the results from the column that was exposed to fire on 4 sides.

The results of this paper found that a column exposed to fire on four sides was the weakest, and a column exposed to fire on 2 parallel sides (the right and left side) was the strongest, with the highest values for the ultimate moment the column supported. If the column was exposed to fire on the compression (top) side and the tension (bottom) side, it was weaker than a column that was exposed to fire on one or neither of those sides. It was also found that a column exposed to fire on the tension side, but not the compression side was weaker than a column that was exposed to fire on the compression side but not the tension side.

Further research should examine concrete columns that are damaged before fire occurs. Reinforced concrete structures must be designed for specific fire ratings, however, the fire resistance of reinforced concrete structures that are subject to damage from seismic activity is not considered during design. Earthquakes can lead to damage in reinforced concrete structures and this damage can affect the fire resistance of concrete and as fire after earthquakes is a real possibility, especially in urban areas, it is important to take this into consideration when designing concrete structures. The reduced fire resistance of these structures can cause the building to collapse much sooner than anticipated and the delays of emergency response teams during earthquakes can make this a catastrophic combination.

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