A review on High Temperature Behavior of a Reinforced Concrete Gable Rafter with Openings

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Abstract: Modern buildings have a lot of ducts and pipelines because they need to have services like air conditioning, electricity, and the phone. These services can be put in place through openings in the webs of concrete beams. One of the problems faced by buildings is exposure to high temperatures. Therefore, adequate structural fire resistance should be provided to resist this situation, or at least allow residents time to escape before stability fails. Very little research has been done regarding reinforced concrete RC beams containing web openings under the impact of high temperatures. The present paper aims to compile this state of work on the performance of RC beams with openings under high temperatures. There are many different topics that will be covered and emphasized like the classification of openings, the behavior of reinforced concrete beams with openings, steel bars and concrete mechanical properties at high temperature, and the performance of reinforced concrete beams subjected to high temperature. Finally, suggestions are made for future studies based on the gaps shown in the existing body of work.

Keywords: Reinforced concrete rafter, Beam openings, High temperature, Gable beam, Fire

1. Introduction

A rafter is one of a set of sloped structural elements such as gable beams that expand from the ridge to the wall plate, downslope perimeter, and that are designed to support the sloped roof and its correlating loads, Figure 1. Piping and ducts are essential in the modern building process for providing basic services including sewage, water supply, air conditioning, and the internet. These ducts and pipes are often installed under the soffit of the rafter and covered by a hanging ceiling, resulting in a dead space on each level; the height of this dead space, which contributes to the overall building height, is determined by the number and size of ducts to be installed. A different arrangement is to pass these pipes through transverse openings in the floor rafters [1]. Design of buildings must provide a suitable fire safety for structural components, because fire is one of the hardest

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environmental conditions that a structure may suffer during its life cycle. The reason for this criterion may be found in the fact that when other fire containment measures fail, structural integrity is a last-ditch effort. One of the problems faced by buildings is exposure to high temperatures. Therefore, adequate structural fire resistance should be provided to resist this situation, or at least allow residents time to escape before stability fails [1]. In this paper, a literature survey that contains a brief review about fire effect on the fire and load caring capacity performance of reinforced concrete rafters and beams with or without openings is presented.

Figure 1: Reinforced concrete rafters.

2. Classification of openings

Definitely the presence of openings in rafter beams make these beams more lightweight, ease of transporting, and geometric flexibility. But it is obvious that, inclusion openings will convert the simple beam behavior into a more complex behavior, as they produce a sudden change in the size of the beam’s cross sections. Nevertheless, the corners of the opening will be affected by high-stress concentrations, which may cause excessive cracking, which is unacceptable from the standpoint of aesthetics and durability. Over time, a continuous beam with lower stiffness may experience excessive deflection under service loads, leading to a significant redistribution of internal stresses, [2].

Prentzas [3] considered openings of various sizes and shapes, including squares, circles, triangles, diamonds, trapezoids, and oblongs, as it shown in Figure 2. The circular opening is the best one.

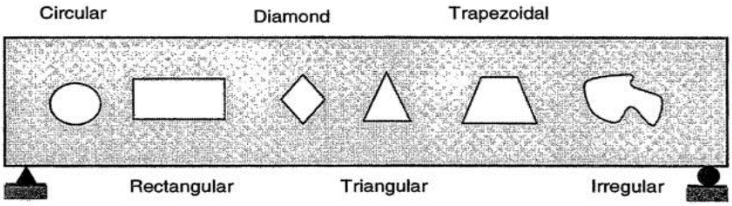


Figure 2: Shapes of opening considered by [3].

According to [4], when the depth d or diameter D of the opening is less than or equal to a quarter of the total depth of the beam H and its width is less than or equal to its depth d, the opening can be regarded as small, as it shown in Figure 3. But when the depth d or diameter D of the opening is greater than a quarter of the total depth of the beam H and its width ℓ is higher than its depth d, the opening can be regarded as large because the insertion of this kind of opening will decrease the strength of the beam and the beam kind behavior will be, as it shown in Figure 4.

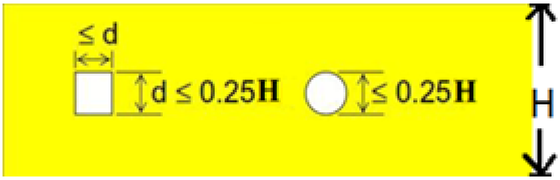


Figure 3: Small openings definition based on openings dimensions, [4].

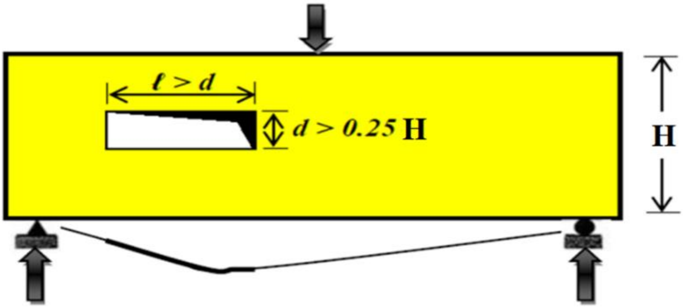


Figure 4: Large openings definition based on openings dimensions, [4].

The opening is considered small when it is small enough to maintain beam-kind behavior, or when the normal beam theory applies. When beam-kind behavior is lost as a result of the presence of openings, the opening is referred to be a large opening. In assuming that Vierndeel action is prevalent and given the fact that failure happens after a 4-hinge mechanism has developed [5], some criteria have been recommended for classifying the dimensions of an opening as small or large. It is assumed that hinges develop in the chord members at a length of half of the depth of beam from the opening's vertical faces. This is illustrated in Figure 5, where h_t or b represents the total depth of a chord, and the subscripts t or b represent the top and bottom chords, respectively.

Small openings, if $Lo \leq h_{max}$

Large openings, if $Lo > h_{max}$

Where h_{max} is the bigger of ht or h_b.

It is assumed in this description that the elements upper and lower the opening have sufficient depth to satisfy the reinforcement detail. For the purpose of determining the value of h_{max} when it comes to circular holes, the circle should be converted to an equivalent square.

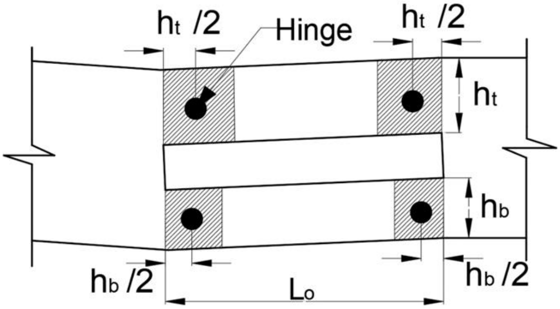


Figure 5: The formation of a hinge in an RC beam with an opening, [5].

According to reference [2] the guidance for determining the size and position of web openings was given, as shown in Figure 6. The authors recommended the following for their study:

(i) The openings in the T-beam should be placed flush with the flange. Rectangular beams often include openings centered on the beam's cross section, although these openings need eccentric depth positioning. The reinforcing bars in the chord components above and below the aperture must have sufficient concrete cover. There has to be enough concrete surfaces on the compression chord element to provide the ultimate compression block during flexure, and there needs to be adequate depth to the element to effectively strengthen against shear forces.

(ii) Openings must not be located nearer to the supports than half of the beam depth (H). This is to avoid shear failures and reinforcing congestion in the critical region. The placement of an opening close to half of the total depth of the beam should also be avoided at any concentrated load.

(iii) The depth of holes should not exceed 50.0% of the entire beam depth.

(iv) The factors limiting the length of a hole are the chord elements' stability, especially the compression chord, and the deflection requirements. If the opening gets greater, several openings with the same passage are preferable to use rather than just an opening.

(v) To guarantee that each opening behaves individually when several openings are utilized, between each pair of holes, the distance between the posts must be no less half the depth of the beam.

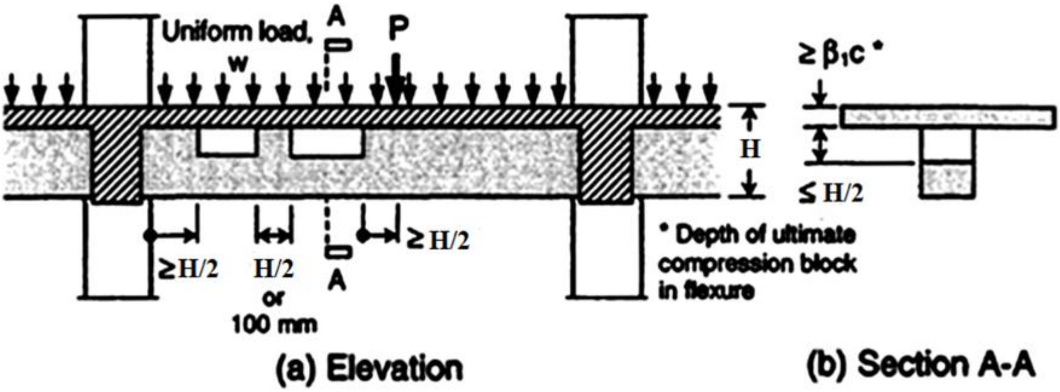


Figure 6: Location of openings guidelines, [2].

3. Behavior of reinforced concrete beams with openings

Abdalla [6] studied the performance of cracking for simply supported pre-stressed concrete beams with quadrilateral openings. The aims of the study were to find; the crack propagation pattern due to the pre-stressing force and due to the vertically applied load and the deflection at the transfer and service load stages. The experimental program included casting and testing 13 posttensioned pre-stressed concrete beams; six of the beams have a rectangular cross-section, five have a T-section and the remaining two were of I-section. A simple design procedure is presented to estimate the cracking load for the various crack patterns and two explicative design examples are given. Test results revealed five types of cracking patterns as shown in Figure. 7. Which were: (a) due to the pre-stressing force at the opening edges, (b) in the corners of the opening area because of the framing action, (c) at the chord elements because of shear, (d) because of bending stresses resulting from secondary moment, in the chord elements, and (e) Because of normal stresses at lower chord elements. The tension cracking and shear cracking can cause the beam to collapse completely. The first of the five types of potential cracking occur at the transfer stage because of the pre-stressing force only, while the other four types occur at stage of the service load. Also, it was noted that the (c and e) types of cracking can lead to the full collapse of the beam, while deep openings may induce the (c and d) types of crack patterns. On the other hand, beams with shallow bottom chords may exhibit the (e) type of crack pattern, in addition the existence of secondary moments near the edges of the opening may cause flange cracking even if it is under compression.

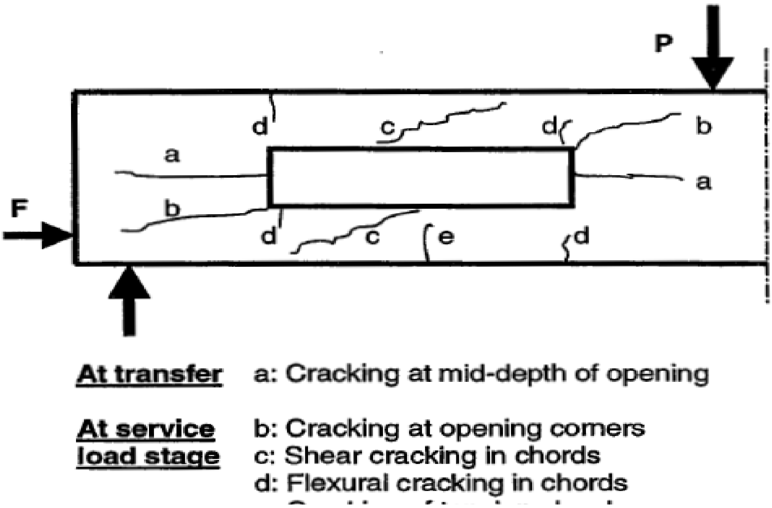


Figure 7: Types of cracking around opening, [6].

Al-Sheikh [7] performed an experiment to examine the behavior of a reinforced concrete beam with various kinds of openings with changing widths at various places. In this experimental research, twenty-seven beams were cast, one of these beams was a solid beam (BN) as a reference beam and the rest beams with the opening. These beams were subjected to four-point loading tests. In terms of ultimate failure loads, deflections, and failure mechanism, the size influence of openings with varied positions was investigated. According to the test results, the ultimate load-carrying strength of the perforated beams at the shear zone was the bigger decrease, whereas at the flexure region. It was a little decrease at most. The Rectangular opening improved the ultimate load reduction over square openings by 4%, whereas the circular openings decreased the ultimate load reduction over square openings by 8%.

4. Exposure to high temperature.

This section discusses in brief the mechanical characteristics of concrete and steel under the effect of elevated temperatures, also the behavior of RC beams subjected to high temperatures and fire models.

4.1 Concrete mechanical properties at high temperature

Koksal [8] revealed that, there were several variables that impacted the behavior of heated concrete. These include the amount of time the concrete was exposed to the high temperature, the rate at which the temperature rose, the maximum temperature it reached, the temperature of the concrete before it was exposed, the degree to which it was saturated with water, the concrete's maturity, the type of aggregate and cement used, the aggregate/cement ratio, and the loading status at the time of exposure. In most cases, a rise in external temperature causes mature concrete to lose some of its mechanical strength.

Kodur [9] studied the characteristics of normal-strength concrete (NSC) at high temperature. Figure 8 shows the temperature effects on the compressive strength of (NSC) normal strength concrete, and Figure 9 shows the Concrete's relative splitting tensile strength at elevated temperature, while Figure 10 shows the Concrete modulus of elasticity at elevated temperature.

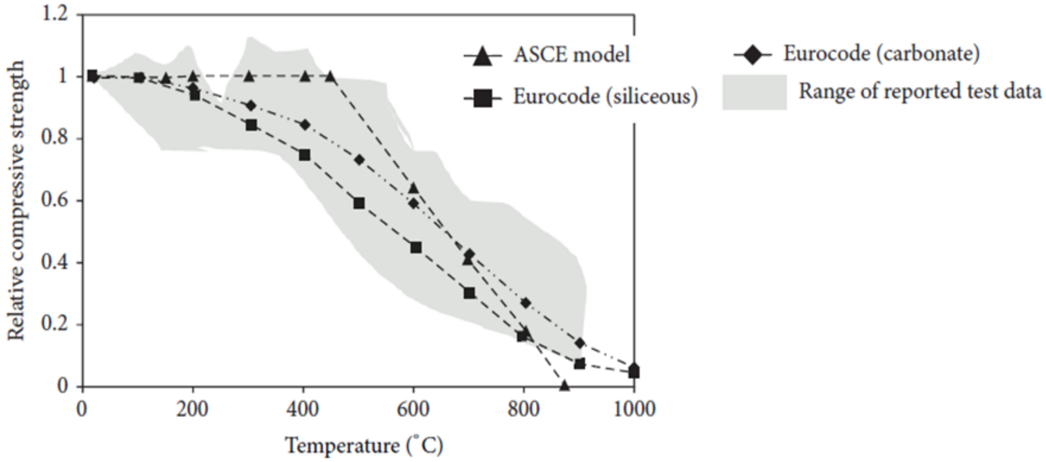


Figure 8: Temperature effects on the compressive strength of (NSC) normal strength concrete, [9].

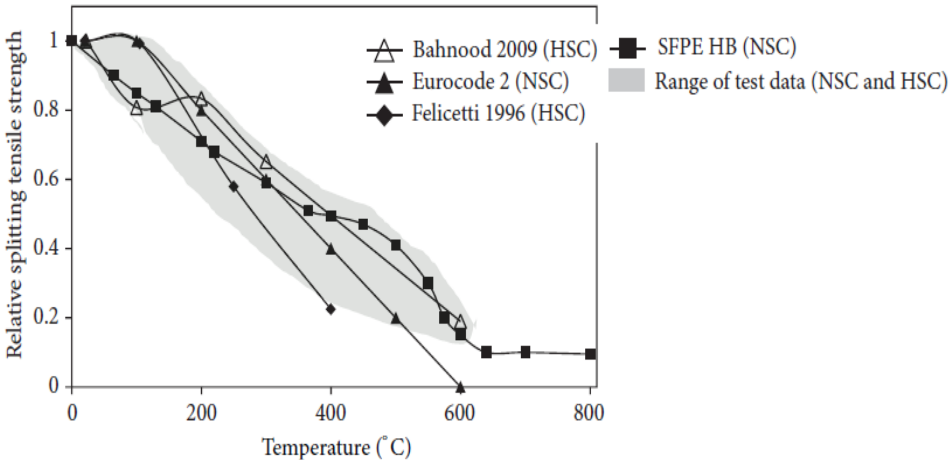


Figure 9: Concrete's relative splitting tensile strength at elevated temperature, [9].

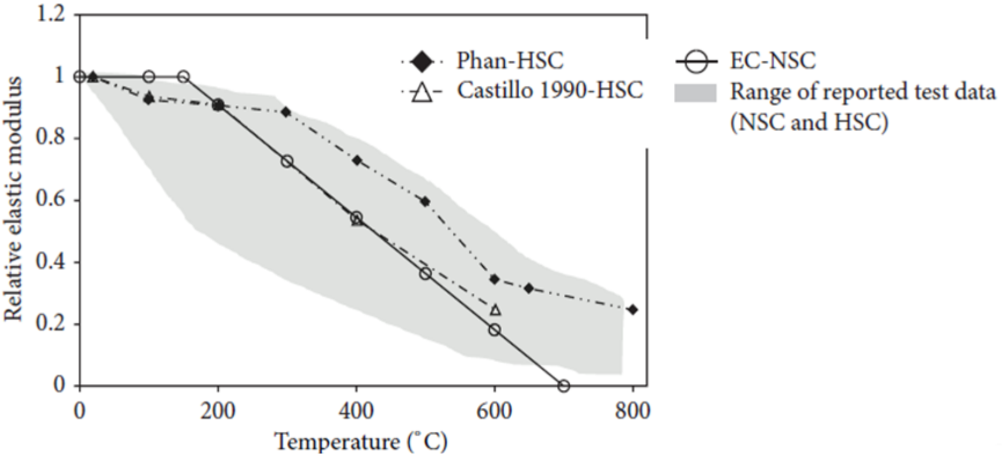


Figure 10: Concrete modulus of elasticity at elevated temperature, [9].

Exposure of normal concrete to burning at about (400.0 and 700.0°C) was given by Abdulkareem [10]. The average residual compressive strength and modulus of elasticity of concrete were 85.30% and 41.40% after 60 minutes of fire exposure to 400.0°C and 700.0°C, respectively; this data was derived through experiments. After being exposed to fire at 400.0 and 700.0 degrees Celsius, the average percentage of remaining splitting tensile strength was 58.10% and 25.10%, respectively, indicating that the splitting tensile strengths is more easily compromised by fire than the compressive strength.

4.2 Steel mechanical properties at high temperature

Holmes [11] studied the effect of high temperature on the stiffness and strength properties of four reinforcing steel bars of varying size. The test programmed was designed to provide data on three major parameters [(yield stress (fy), ultimate strength (fu), and elastic modulus (Es)]. They found that the normalized results for the fy, fu and Es for all sizes are as follows:

1- There was no significant change in the normalized value below 300°C.

2- A 50% reduction in both the yield stress and ultimate strength was obtained between (520°C – 580°C), and between (540°C – 700°C) for the elastic modulus.

Abramowicz [12] observed that when the temperature of steel rises, its yield strength and elasticity modulus decrease dramatically. However, after the building has cooled down after a fire, the reinforcing steel has often regained most of its material qualities. Those warnings come into play when the reinforcement in certain structural parts may become worthless after being exposed to fire and the bar anchoring fails.

Qiang [13] studied the mechanical characteristics degradation of high-fire strength steels. Following cooling from highest temperatures up to 1000 oC, tensile strength tests were carried out on 2 commonly used steel grades 460 and 690MPa. This investigation was used to acquire the post-fire modulus of elasticity, yield strength and ultimate strength, and stress-strain curves. The mechanical characteristics of high-performance steels after fire differ from those of mild steels. For evaluation of S460 and S690 mechanical characteristics following a fire, two different sets of prediction equations were developed, which are well consistent with the test results. See Figures 11 and 12.

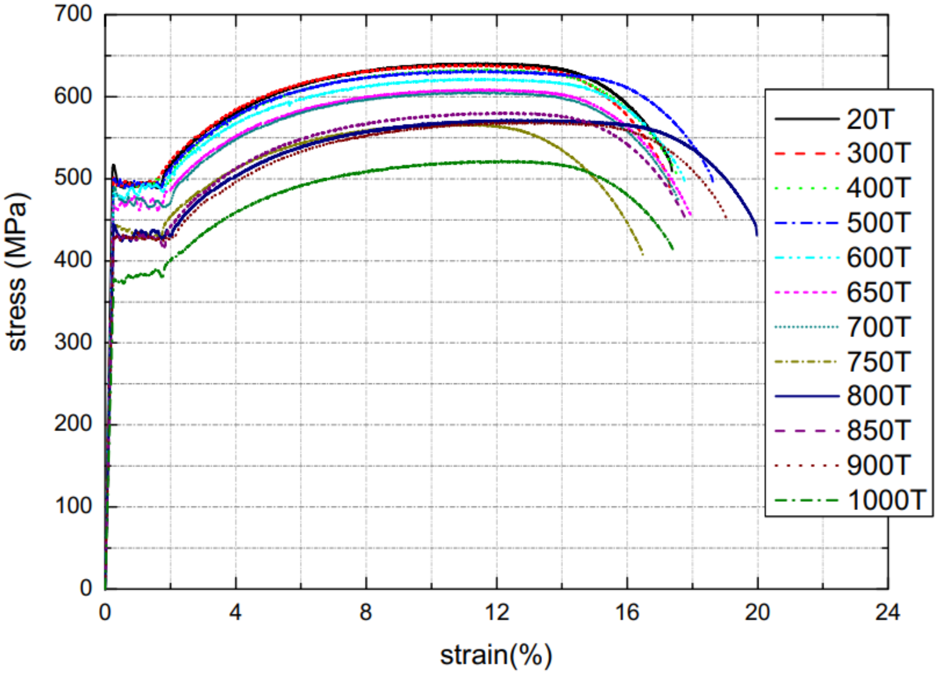


Figure 11: Stress–strain curves of grade 460MPa after being exposed to a range of fire temperatures. [13].

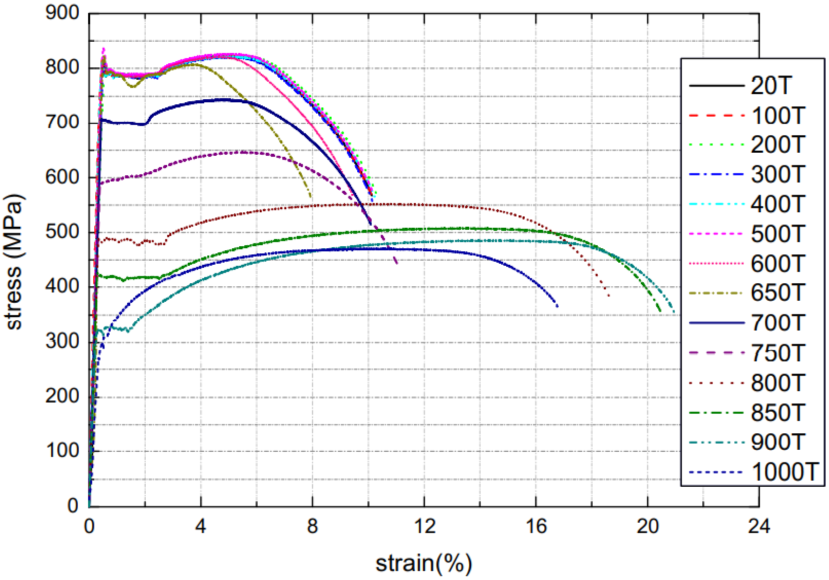


Figure 12: Stress–strain relationship of grade 690 after being exposed to a range of fire temperatures. [13].

The findings of exposing two kinds of steel reinforcement to elevated heat (400.0 and 700.0°C) were given by Abdulkareem [10]. Others were exposed right away to high temperatures (400.0 and 700.0°C), while others were protected by a layer of concrete (15 mm) as a cover. From the test findings of fire exposure for 60 minutes at 400.0 and 700.0°C and gradual cooling, it was determined that the residual average percentage of yielding tensile stress of (12 mm bar) was 96.60 and 86.40% for bars protected by concrete cover and 93.40 and 81.30% for bars not covered, while the residual average percentages of the ultimate tensile strength (12 mm bar) was 94.0 and 81.0%, for bars protected by concrete cover, and 91.0 and 75.0% for an uncovered bar.

5. Performance of reinforced concrete beams subjected to high temperature

Kodur [14] provided a technique to assess the fire performance of beams enhanced by fiber-reinforced polymer (FRP) as near-surface mounted (NSM) fiber. The model is built on the macroscopic method to finite elements and is able to track the NSM FRP enhanced RC beam behavior from preloading to failure under a certain fire scenario and loading types. The model is designed for elevated temperature characteristics, real load, and temperature-induced deterioration of the bonding at the FRP interface. The model validity is determined by comparing model results with data from tests of ambient and burned samples. The verified model was utilized in numerical experiments for the comparison of the fire behavior of concrete samples with different kinds of reinforcement and isolation systems. According to numerical simulation, a concrete beam reinforced with NSM FRP reinforcement has somewhat lesser fire resistance than a typical RC beam but greater fire resistance over externally bonded FRP. Also, it is demonstrated that the proper placement of NSM FRP and an insulation system may improve the fire resistance of RC beams reinforced with NSM FRP reinforcement.

Kadhum [15] studied the influence of fire flame burning on the response and ultimate load of RC beams with rectangular section. Beam models of a smaller scale were proposed. Five end restraint beams casting and testing at the age of sixty days, the specimens were exposed to burning temperatures up to 750°C. Two temperature targets of 400 and 750°C were selected, with an exposure period of 1.5 hours. The rectangular RC beam with length = 225 cm, width = 37.5 cm, and height = 37.5 cm were cast and exposed to fire. The findings of the tests show that the rigid beams cooled in water had a significant reduction in ultrasonic pulses velocity and rebound numbers, which was (2-5 percent) in excess of the rigid beams Allowed to cool by the air. Load-deflection graphs show a harmful response to fire exposure, (Figures 13 and 14).

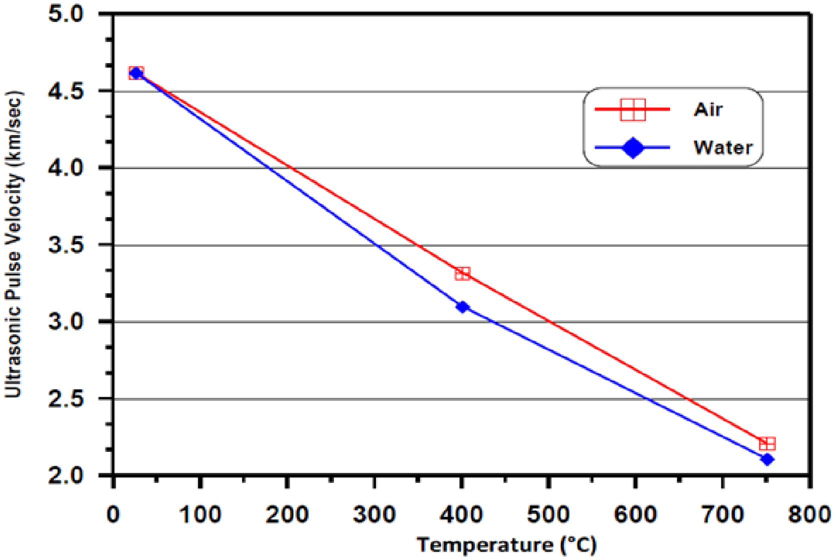


Figure 13: The effect of fire flame on the UPV, [15].

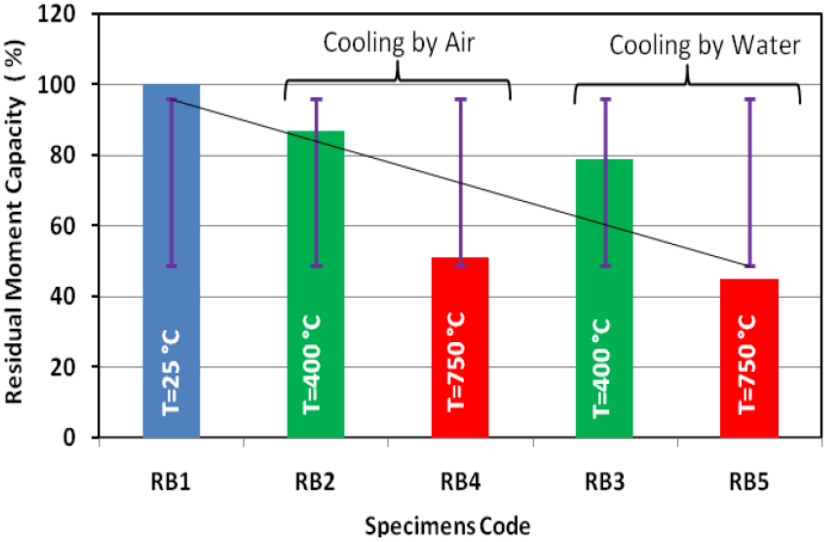


Figure 14: The decreases in residual moment capacity with fire [15].

Kodur [16] provided a technique for measuring fire exposed reinforced concrete beams' residual load carrying capacity. The technique comprises the capture of RC beam responses in 3 stages: the structural responses at room temperature, thermo-mechanical behavior under fire, and post-fire residual responses after beams have cooled down. During the heating and cooling stage of fire exposure, and the residual (after cooling) stage of analysis, separate material characteristics of the reinforcement steel and concrete are tested. The residual responses of fire-exposed reinforced concrete beams also include the load intensity, scenario of fire, and plastic deformations which develop in the RC beams throughout fire exposure. The suggested approach is realized using a numerical model developed in computer software ABAQUS. Numerically predicted values demonstrate an acceptable agreement with the response variables determined by the tests to assess the residual capacity of burned beams. Additionally, the numerical analysis' residual capacity estimations are compared to the results of a simplified sectional study that takes maximum reinforcing bar temperatures into account. This comparison demonstrates that numerical analysis produces more realistic residual capacity estimates than simple sectional analysis, (Figures 15 and 16).

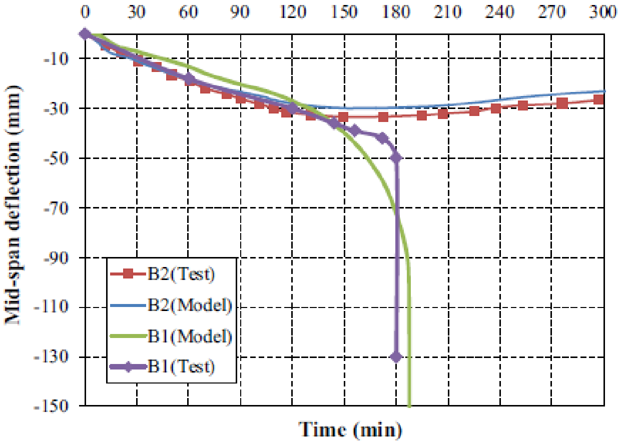


Figure 15: Comparisons of the estimated and measured deflection of mid-span for RC beams Throughout fire exposure, [16].

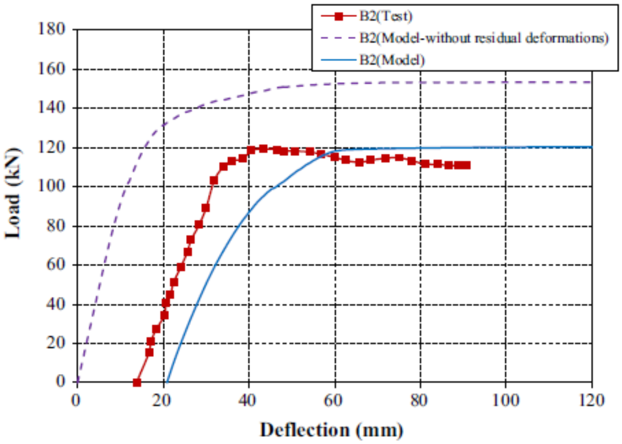


Figure 16: Comparisons of the estimated and measured residual load-deflection relationships, [16].

Abdulkareem [17] investigated the behavior of gable RC beams solid and included trapezoidal holes when subjected to the burning. The experimental plan consists of the casting and testing of 9 gable RC beams organized into three primary groups. Each group had three gable RC beams and was classified according to burning temperature (ambient lab temperature, 400.0 °C, and 700.0 °C) (solid beams and beams with six and eight trapezoidal openings). For samples with identical shapes, raising the burning temperature tends to result in their degradation, as seen by their rising mid-span deflection during the fire exposure time and their residual deflection subsequent to chilling, while the situation with the existing holes is exacerbated. Then, the burnt gable RC beams were progressively cooled by exposing them to ambient laboratory conditions and were then loaded till failure. By trying to compare these rafters to unburned reference rafters, the impact of temperature on the remaining ultimate load-bearing capability of each rafter was investigated. The ultimate strength of solid gable RC rafters subjected to 400.0 °C and 700.0 °C temperatures decrease by around 5.70% and 10.83%, respectively. Under the same burning circumstances, the ultimate strength of gable RC beams with trapezoidal holes decreased by 21.14% and 32.7% (for rafters with eight openings) and 28.0% and 34.3% (for rafters with six openings). Under identical burning circumstances, the excessive midspan deflections for these three kinds of rafters ranged from 2.0% to 30.7%, 1.330 to 21.80%, and 1.50% to 17.80%. Figures 17, 18, and 19 show the load-midspan deflection curves for all samples examined.

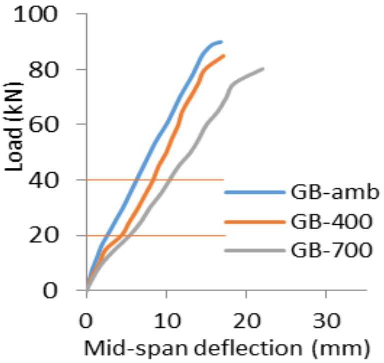


Figure 17: Load-deflection curves solid rafters group , [17].

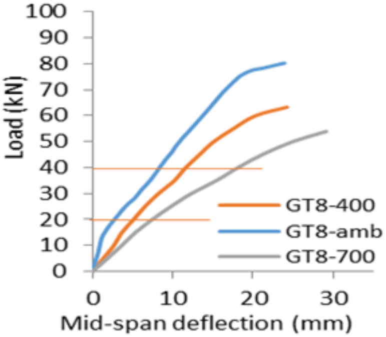


Figure 18: Load-deflection curves rafters with 8 openings group, [17].

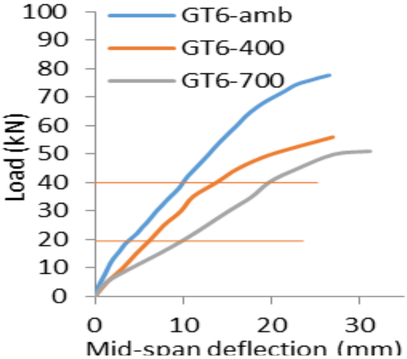
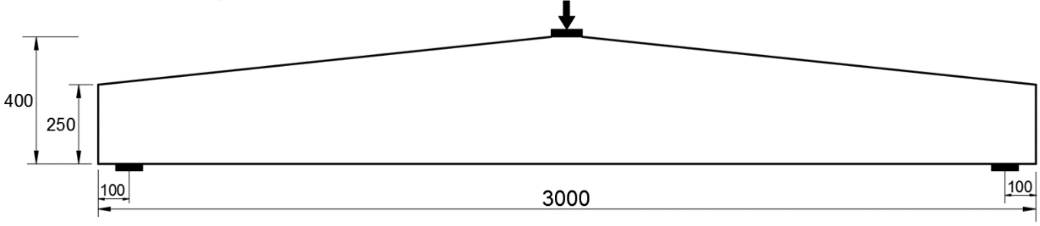


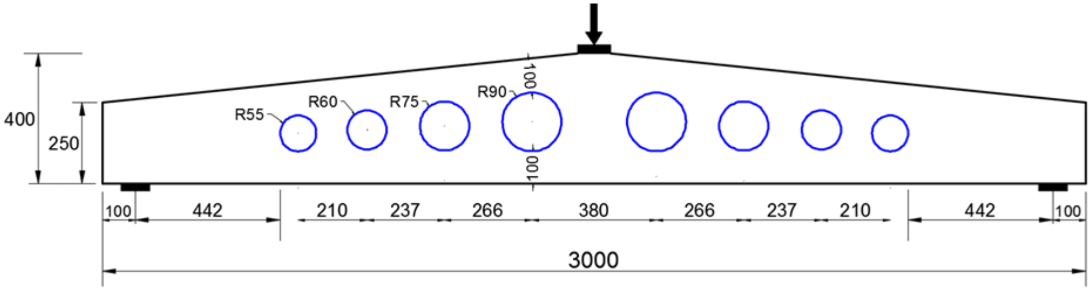
Figure 19: Load-deflection curves rafters with 6 openings group, [17].

It is worth to note that, the effect of high temperature changes the mode of failure in perforated rafters and reduces the ultimate load clearly, where the mode of failure in burned perforated rafters was with diagonal cracks starting from the top corner of the before the end opening, expanded through the adjacent last posts forward for the bottom corner of the end openings, frequent in the adjacent next two openings, then following by concrete crushing of the last opening top chord.

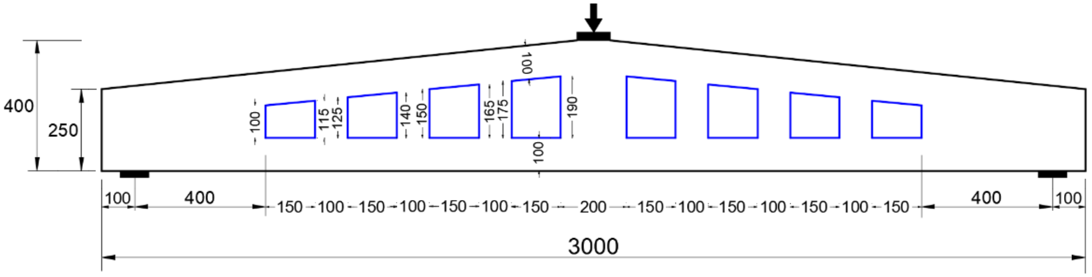
After burning, the performance and residual strength of non-prismatic reinforced concrete (NPRC) rafters solid and including holes were studied by Abdulkareem [18]. Three non-prismatic rafters were used throughout the three temperature target groups (ambient lab, 400.0, and 700.0 degrees Celsius) (solid, eight trapezoidal openings, and eight circular openings). Assuming the same rafter geometry, experiments showed that NPRC rafters deteriorated as burning temperatures increased, as seen by an increase in mid-span deflection during the fire exposure duration and residual deflection after cooling. However, the problem of pre-existing gaps just has become worse. After being burned, NPRC rafters were gradually cooled to ambient temperature in the lab, where they were loaded to failure in order to compare their residual ultimate load-bearing to that of control beams that had not been burned. It was found that the ultimate strength of solid NPRC rafters subjected to temperatures of 400.0 and 700.0oC decreases by 5.70 and 10.840 percent, respectively, when compared to unburned rafters, while the ultimate strength of NPRC beams with 8 trapezoidal openings decreases by 21.14 and 32.81 percent, and the ultimate strength of NPRC beams with 8 circular openings decreases by 10.51 and 12.81 percent. The longitudinal compressive strain of Group ambient in the midspan of solid rafters reaches 2700.0 at a higher loading stage, whereas other rafters with holes indicate divergent strain more than that, at roughly 3000.0. The lower chord's primary reinforcements, meanwhile, have reached or beyond their yield points. Rafters' stiffness is altered by heat exposure, reducing their load-bearing capacity and, in combination with premature failure, reducing the strain at the end of the process. The plan of the beams is shown in Figure 20.



a-Solid non-prismatic beams NPS, NPS-400, and NPS-700



b-Non-prismatic beams with circular openings shape NPC, NPC-400, and NPC-700



c-Non-prismatic beams with trapezoid openings NPT, NPT-400, and NPT-700

Figure20: beams layout [18].

As seen in Figure 21, the rate of the transitional time to achieve the target burning temperature of 400.0 and 700.0°C was 6.9 and 10.0 minutes, respectively, equivalent to the rate of ASTM E-119 [19]. And Figure 22 illustrates the impact of temperature on deflection under applied load.

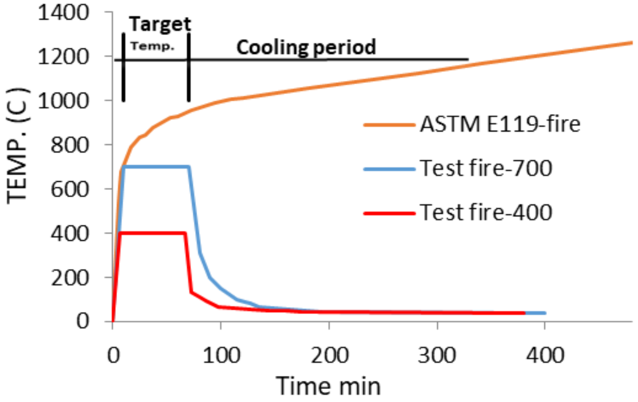
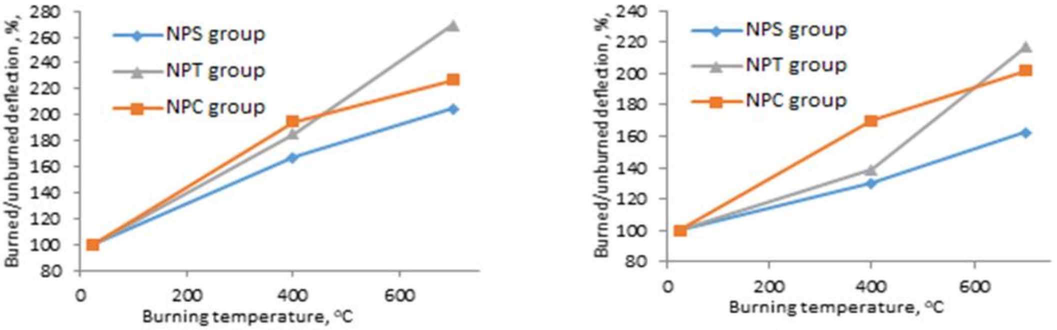


Figure 21: Fire scenario employed for the burning test [18].



a- At 20 kN b- At 40 kN

Figure 22: Impact of temperature on applied load deflection, [18].

6. Conclusions and Future Works

This study examines previous research on RC rafters with holes under the influence of high temperatures. It is obvious from the preceding review that there are research gaps that need to be studied. The following are the primary topics that might be regarded as conclusions and recommendations for future study as a means to address the gaps in the current subject.

1. The negative effect of high temperature changes the mode of failure in perforated beams and reduces the ultimate load clearly.
2. Using circular openings instead of trapezoidal one’s produces increasing in strength for unburned and burned beams. The circular openings give an improvement in ultimate load carrying capacity.
3. The testing of assessment of the fire performance of a structural element is very complicated and depends on many variables like fire scenario, target temperature, loading conditions, time of burning, method and time of cooling, temperature-time relationship, furnace or chamber type, and fuel type.
4. Future work must cover studying the behavior of perforated prestressed concrete rafter under the effect of high temperature (350-800^{o}C).
5. Future work must also cover studying the behavior of perforated prestressed concrete rafter by increasing upper chord (T-shaped or I-shaped beams) under fire effect.
6. An experimental and finite element models are needed to study the performance of fibrous reinforced SCC rafters under the effect of high temperature.

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مراجعة لسلوك العتبات الجملونية الخرسانية المسلحة ذات الفتحات تحت تاثير درجات الحرارة المرتفعة

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المستخلص: تحتوي المباني الحديثة على الكثير من القنوات وخطوط الأنابيب لأنها تحتاج إلى خدمات مثل تكييف الهواء والكهرباء والهاتف. يمكن وضع هذه الخدمات من خلال فتحات في شبكات العتبات الخرسانية المسلحة. من المشاكل التي تواجه المباني هي التعرض لدرجات حرارة عالية. لذلك، يجب توفير مقاومة هيكلية كافية للحريق لمقاومة هذا الوضع، أو على الأقل السماح للسكان بوقت للهروب قبل انهيار المبنى. تم إجراء القليل جدًا من الأبحاث حول عتبات الخرسانة المسلحة التي تحتوي على فتحات تحت تأثير درجات الحرارة المرتفعة. تهدف هذه الورقة إلى تجميع الابحاث السابقة والخاصة بأداء العتبات الخرسانية المسلحة ذات الفتحات تحت درجات حرارة عالية. هناك العديد من الموضوعات المختلفة التي سيتم تغطيتها والتأكيد عليها مثل تصنيف الفتحات، وسلوك الكمرات الخرسانية المسلحة مع الفتحات، وقضبان الصلب والخواص الميكانيكية للخرسانة عند درجات الحرارة العالية، وأداء العتبات الخرسانية المسلحة المعرضة لدرجة حرارة عالية. أخيرًا، يتم تقديم اقتراحات للدراسات المستقبلية بناءً على الثغرات الموضحة في مجموعة العمل الحالية.

الكلمات المفتاحية: عتبة خرسانية مسلحة، العتبات ذات الفتحات، درجة حرارة عالية، العتبة الجملونية، النار

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