Tikrit Journal of Engineering Sciences (2022) 29 (4): 56-68
DOI: http://doi.org/10.25130/tjes.29.4.7

IRAQI
Academic Scientific Journals

College of Engineering

ISSN: 1813-162X (Print); 2312-7589 (Online)
Tikrit Journal of Engineering Sciences
available online at: http://www.tj-es.com

TJES
Tikrit Journal of Engineering Sciences

Behavior of Reinforced Concrete Members Exposed to Fire: Review Article

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Keywords:
Fire exposure; Fire Resistance; High Temperatures; Reinforced concrete; Structural elements; Thermal Impact

ARTICLE INFO

Article history:
Received 13 Oct. 2022
Accepted 14 Dec. 2022
Available online 27 Dec. 2022

Citation: Klak FS, Jomaah MM, Ahmad S. Behavior of Reinforced Concrete Members Exposed to Fire: Review Article. Tikrit Journal of Engineering Sciences 2022; 29(4): 56-68.
http://doi.org/10.25130/tjes.29.4.7

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Subject Area

Civil and Structural Engineering

ASJC Code:2205

ABSTRACT

Fire is one of the most severe conditions to which buildings may be exposed. However, reinforced concrete has good resistance, which makes it one of the building materials most widely used worldwide. When reinforced concrete is exposed to high temperatures, its skeletal members undergo changes that may lead to, in many cases, inclusive cracking. Beams, columns, and slabs are the most important structural elements in any concrete construction. Structural members are generally designed to satisfy the requirements of serviceability and safety limit states for various environmental conditions. Typically, structural members are created to meet a specific fire resistance grade. The characteristics of the structure and the type of occupation are just two variables that affect fire resistance. Structural fire rating's primary goals are to enable building inhabitants enough time to leave, enough time for firefighters to put out the fire, and enough time to prevent any potential structural damage. This article overviews how various reinforced concrete building structural elements behave when exposed to high temperatures. It has been found that both concrete and reinforcing bars are adversely affected by fire. Furthermore, it has been discovered that flexibility and stiffness decrease with increasing stress or the period of fire exposure. Also, the flexibility and stiffness rise with increasing structural element cross-section; however, the maximum slab deflection non-linearly decreases during the fire test. The bottom of the concrete slab begins to cool as temperatures decrease, which increases the yield strength of the bottom reinforcing and causes it to contract along with the lower half of the slab. This article also presents a review of a set of experimental and theoretical results on the thermal behavior of reinforced concrete slabs, beams, and other structural parts under different conditions and scenarios as a historical review.

سلوك الاعضاء الخرسانية المسلحة المعرضة لتأثير الحرائق: مراجعة متقدمة في الادبيات

فادية سعدي كلاك قسم الهندسة المدنية/ كلية الهندسة / جامعة تكريت / تكريت - العراق.
ميسر محمد جمعه قسم الهندسة المدنية/ كلية الهندسة / جامعة تكريت / تكريت - العراق.
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الخلاصة

تعتبر النار من أشد الظروف التي قد تتعرض لها المباني. على الرغم من أن الخرسانة المسلحة تتمتع بمقاومة جيدة، مما يجعلها واحدة من أكثر مواد البناء استخدامًا في جميع أنحاء العالم، فعند تعرضها لدرجات حرارة عالية، تخضع أعضائها الهيكلية لتغييرات قد تؤدي، في كثير من الحالات، إلى تشققات خطيرة. تعتبر العتبات، الأعمدة، والألواح من أهم العناصر الهيكلية لأي بناء خرساني. يتم تصميم الأعضاء الهيكلية بشكل عام لتلبية متطلبات الخدمة وحالات حد السلامة لمختلف الظروف البيئية. عادة، يتم إنشاء أعضاء الهيكل لتلبية درجة مقاومة حريق محددة. إن خصائص الهيكل ونوع الوظيفة التي يؤديها هما المتغيرين الذين يؤثران على مقاومة الحريق. تتمثل الأهداف الأساسية لتصنيف الحرائق الإنشائية في: اعطاء سكان المبنى وقت كافٍ للمغادرة، وتوفير وقت كافٍ لرجال الإطفاء لإخماد الحريق، ووقت كافٍ لمنع أي ضرر هيكلي محتمل. تتناول هذه المقالة نظرة عامة على كيفية تصرف مختلف العناصر الهيكلية للبناء الخرساني المسلح عند تعرضها لدرجات حرارة عالية. لقد وجد أن كلا من الخرسانة وقضبان التسليح تتأثر سلبًا بالحريق. علاوة على ذلك، تم اكتشاف أن المرونة والصلابة، التي تقل مع زيادة الإجهاد أو زيادة فترة التعرض للحريق، تزداد مع زيادة المقطع العرضي للعنصر الإنشائي، على الرغم من أن الانحراف الأقصى للبلاطة يتناقص بشكل غير خطي أثناء اختبار الحريق. وحالما تبدأ درجات الحرارة بالانخفاض، يبدأ الجزء السفلي من البلاطة الخرسانية في البرودة مما يزيد في خضوع التسليح متسببا في تقلصه مع النصف السفلي من البلاطة. تقدم هذه المقالة أيضًا استعراض لمجموعة من النتائج التجريبية والنظرية حول السلوك الحراري للعتبات والألواح الخرسانية المسلحة والأجزاء الهيكلية الأخرى في ظل ظروف وسيناريوهات مختلفة كمراجعة تاريخية.

الكلمات الدالة: الخرسانة المسلحة، العناصر الإنشائية، التعرض للحريق، مقاومة الحريق، التأثير الحراري، درجات الحرارة العالية.

1.INTRODUCTION

Fire safety is essential to ensure property and life protection. Building fires can occur at any time; thus, protecting the residents and preserving the structure's integrity is crucial. Recently, many fires occurred, including fires on concrete structures, which confirmed that the concept of fire resistance is significantly limited. However, significant concrete deterioration occurs due to a fire that may threaten the safety of installations in previous fire incidents. To record the history of the structural reaction in reinforced concrete elements (structures) subjected to fire over a brief period, investigations were done for deformations, stresses, cracking, loss of stiffness, and strength of reinforced concrete frame structures. Becker and Bresler [1] performed a two-stage analysis using finite element software. The thermal impacts were considered, then the structural response was calculated. The program was based on numerical procedures. The study showed that it was possible to obtain the deformed geometries that equalize the forces caused by the applied loads and interior strains besides deterioration by employing an iterative technique within time increments. Hertz [2] discussed the properties of concrete materials at high temperatures. Also, equations were developed to describe the final boundary condition analyses of "rectangular beams, slabs, T-sections, walls, and rectangular columns" at any period of any kind of fire. The described technique was to design a structure for different fire exposure scenarios. Also, the behavior of 3D reinforced concrete structures in a fire was predicted by developing the Finite Element Thermal Computing Program (TEMP) and Structural Computing (STRUCT) [3]. First, the date of temperature distribution was determined using nonlinear thermal analysis. Then, differences in the stiffness matrix caused by variations in material characteristics were calculated. Consequently, static analysis was implemented in terms of time intervals up to failure. Shi et al. [4] compared the force temperature trajectories. The force temperature trajectories are expressed as the trajectory of constant forces but exposed to an elevated temperature that produced an F.T. path, "the path of constant forces but subjected to elevated temperature", and a trajectory having a constant temperature yet being affected by the T.F. route "the path of constant temperature but subjected to applying forces". A 2000 kN hydraulic test machine, with an electric furnace and closed-loop servo control, was used to subject 13 beam samples to two principal paths. According to the results, the F.T. path's fire resistance differed from the T.F. path. Shi X et al. also tested in another paper [5] six specimens with dissimilar thicknesses of the concrete cover. The authors examined the concrete cover effects on the reinforced concrete, exposure to fire, and flexural elements properties. The specimens were subjected to fire at the bottom face and the two lateral faces. The results showed that the bottom concrete cover significantly influenced the ultimate loading capacity; however, increasing the concrete cover thickness decreased the degree of this influence. Hence, it is inappropriate to improve the fire resistance of the specimen by overly increasing the thickness of the bottom concrete cover. Compared with the bottom concrete cover, the lateral concrete cover had an insignificant practical effect on the fire resistance of the specimen. Elghazouli and Izzuddin [6] focused on the failure case with rupture in reinforcement associated with the performance of lightly reinforced concrete elements subjected to fire conditions, using an analytical model to conduct a parametric investigation. The results indicated that besides the effects of temperature, other factors had a significant and direct influence on failure, i.e., the properties of the bond, the length of the member, and the response of the steel material. The penetration depth was discovered to be proportional to the temperature of the fire, and the fissures often ran rather deep into the concrete component. Most of the damage was limited to the surface near the fire's origin; however, the type of cracking and discoloration of the concrete indicated that the concrete around the reinforcement had reached 700 °C. Cracks that reached more than 30 mm into the structure's depth were attributed to a brief heating/cooling cycle caused by the fire's extinguishment. These findings were a case study of cracking in a fire-damaged concrete structure, focusing on the depths to which fractures penetrate the concrete [7]. Another summary of the behavior of different structural components of reinforced concrete buildings under elevated temperatures was presented by Ahmad and Sadique [8]. It was observed that concrete was affected more than the reinforcing bars when the structure was exposed to fire. It was also observed that the load level and axial constraints slightly affected the R.C.C. beams' thermal response. The fire resistance of concrete depended on the fire's duration and the exposure temperature. An enhanced effect on strength was obtained by increasing the exposure time when the heating temperature was low. While increasing the heating temperature demonstrated the effect of degradation. Longer exposure times paired with greater temperatures caused decreased Young's modulus and Poisson's ratio contributing to the degradation effect. For lower heating temperatures, a longer exposure time positively impacted all strengths and fracture toughness; however, the impact is detrimental for higher heating temperatures, as claimed by Zhang B. [9]. Overall, it is evident that the concrete's fire performance must be considered a critical design aspect with the current high-strength concrete construction. Also, the structural parts must be able to sustain dead and live loads without collapsing when concrete is subjected to fire. Additionally, as part of a quality assessment similar to this, reasonable rules and standards for practical application should be produced with proper empirical evaluation on a laboratory scale.

2.BEHAVIOUR OF REINFORCED CONCRETE BEAMS EXPOSED TO FIRE

2.1.Isolated Reinforced Concrete Beams

Several fire tests on reinforced concrete beams have been conducted over the last three decades at the Portland Cement Association's Fire Research Laboratory, Technology Laboratories, Inc., Skokie, 111. All those tests were performed using ASTM Designation E l19 Standard exposure to fire. In their article, Ellingwood and Lin [10] performed thermal tests, one of which was reinforced concrete, by testing six continuous beams in fire experiments. Three of those beams were proposed to determine the effect of concrete cover on beam behavior. In contrast, the fourth model had a larger area to check the shear stresses under the fire effect, then all four beams were checked according to ASTM E119 fire exposure. Meanwhile, the two remaining beams were subjected to severe fire for a short period (SDHI) exposure. The study showed that during the first three hours of the fire, the effects of the thickness of the concrete cover on the deflections of the beams were minimal, Fig. 1. Shear cracks appeared as early as about ninety minutes after the onset of the fire. In contrast, the flexural cracks appeared after about half an hour, and then they spread rapidly in all the beams resulting in their failure to flex rather than to shear off. This observation indicated that the beams' shear strength was insignificant at high temperatures - despite the sizeable internal faulting caused by nonlinear stress gradients. El-Hawary et al. [11] prepared four reinforced concrete beams of (200 * 120 * 1800) mm dimensions. Three of them were tested after one day of burning in a standard burning chamber for three identical periods of 30, 60, and 120 minutes. One beam was unburned and used as a reference in terms of resistance to compression. The resistance compression was based on the standard ultrasonic pulse and Schmidt hammer rebound non-destructive tests in which the recorded measured responses were related to bending strength, strains, deflections, deformations, and crack patterns. Inversely with exposure time, the effect of fire on concrete was more extensive than that on steel reinforcement, which increased the compressive strain more significantly than the tensile strain, Figs. (2-5). At the beginning of the previous twelve years, Khan et al. [12] investigated reinforced concrete beams in the tension zone only and with specifications identical to the concrete used in clinker silos, nuclear containment, and stacks by subjecting them to cycles of burning at different temperatures (100, 200, and 300 °C) and cooling for diverse periods (7, 14, 21, and 28 days), as shown in Fig. 6. The highest failure of the beams was caused by the development of inclined shear cracks that occurred through the load application point. The initial flexural crack load percentage of beams exposed to thermal cycles of 300 °C was significantly influenced and decreased with an increase in the number of cycles; however, it was essentially unaffected by the number of cycles at peak temperatures of 100 and 200 °C. They discovered that for 100 °C and 200 °C peak-heated beams, the maximum shear strength of reinforced concrete beams subjected to heat increased by 10% with increasing thermal cycles, but it declined by 14% for the 300 °C peak-heated beams at higher thermal cycles. Also, it was observed that the shear strength loss occurred due to temperature rise and thermal cycles increase as a result of the drying of the cement paste, which led to its gradual disintegration and the appearance of micro-cracks due to tension in the surrounding concrete. Thus, it was concluded that the stress concentrations at the edges of the critical cracks led to a further deterioration in the strength, Fig. 7.

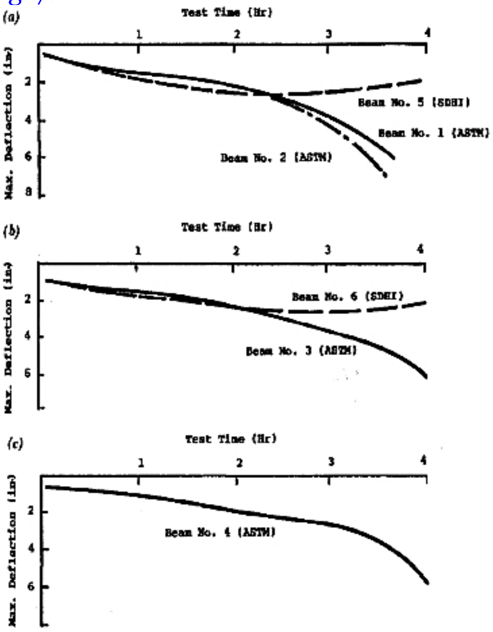


Fig. 1 Measured Maximum Deflections during Fire Tests [10].

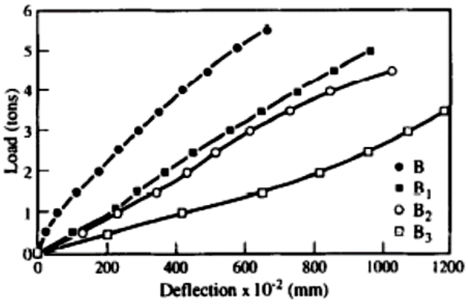


Fig. 2 Load – Maximum Deflection [11].

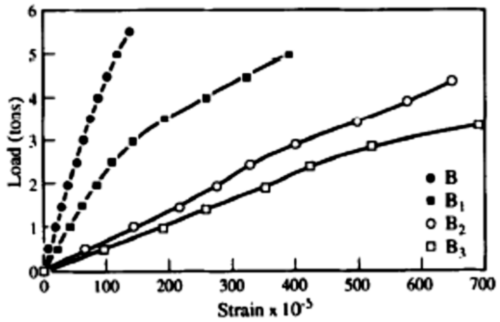


Fig. 3 Load- Maximum Compressive Strains [11].

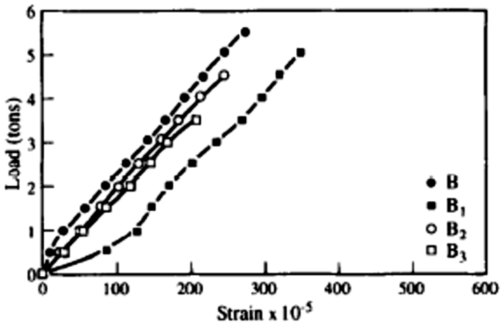


Fig. 4 Load- Maximum Tensile Strains [11].

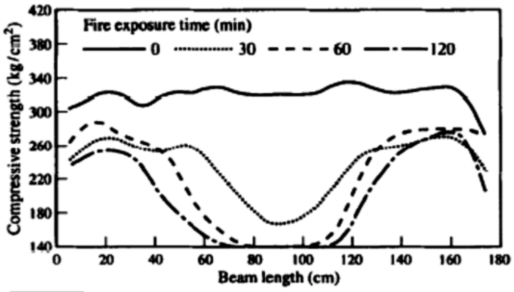


Fig. 5 Compressive strength along Beams exposed to fire at the middle zone [11].

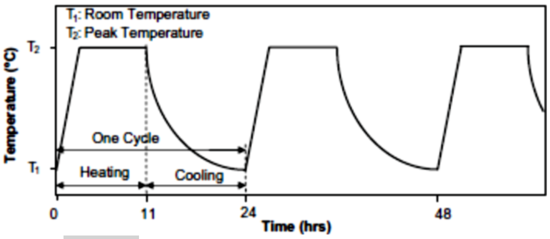


Fig. 6 Heating-Cooling Cycles (T1 = 27 °C, room temperature) [12].

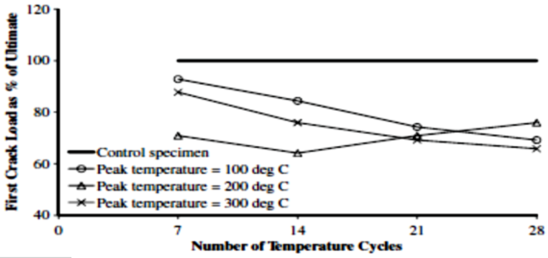


Fig. 7 Relative variation of the shear capacities for the four heated beams of Khan et al. 2010 with their elevated temperatures and numbers of cycles [12].

Another study by Song et al. [13] introduced six full-scale beams designed based on weak shear and strong bending to evaluate their resistance to fire and loads by subjecting them to an impact load initially followed by exposure to combustion from three sides with a fixed load. The studied variables were the efficacy of the stirrup ratio and the longitudinal reinforcement ratio. It was found that the deflections initially increased slowly up until a certain point when their expansion became sharp. In the cases of that observation, it was indicated that with the increase in the proportion of longitudinal reinforcement, the sample's failure rate increased; that is, the longitudinal reinforcement could have a significant pinning effect, which improved the shear capacity of the sample at high temperature. The authors concluded that while the stirrup configuration effectively reduced the brittle change of vertical displacement when the beam entered the failure phase, there was an insignificant uniform effect of the stirrup ratio on the reinforced concrete beam’s resistance under fire exposure if the imposed load ratio remained constant. Finally, based on the principles of "strong bending and weak shear", they declared that the failure of a simple reinforced concrete beam supported by stirrup reinforcement at room temperature was a shear failure. At higher temperatures, the failure mode might be a shear-bending failure. Beams internally made of reinforced concrete with various reinforcements (F.R.P.) were presented in an article [14] to examine their abilities to resist residual thermal stresses after exposure to high temperatures that reflect the fire's conditions. It was used three distinct types of F.R.P. rods for reinforcement: "(1) basalt-FRP (BFRP), (2) hybrid F.R.P. with carbon and basalt fibers (HFRP), and (3) nano-hybrid F.R.P. (F.R.P.)", all of which were attached to steel reinforcement using a modified epoxy matrix. Before heating the beams in the furnace and allowing them to cool, they were unloaded halfway to their maximum strength capacity. Then, the beams were flexurally reloaded till failure. An unusual phenomenon was noticed as the deflection decreased after a specific temperature in HFRP rods and nHFRP-reinforced rods. The authors proposed that this phenomenon was related to the thermal expansion coefficient of the carbon fibers in the HFRP and nHFRP filaments, where creep can appear in those fibers, causing the prestressing effect. The effect of the inclusion of hybrid fibers (steel and polypropylene) on the strength of R.C. beams exposed to elevated temperatures was studied by [15, 16]. Different percentages of fibers were used in the tested beams. The beams were subjected to service load, and then controlled fire was applied for 120 min by the temperature-time curve prescribed in ASTM E-119. The results showed that the inclusion of fibers increased the R.C. beam's resistance strength to elevated temperature and reduced deflection, which could considerably improve the residual stiffness of fire. A study introduced by Ibraheem and Abdullah [17] experimentally examined the fire response of steel beams subjected to bending and shear-dominating stress. The specimens were all the same length of 1250 mm. The total depth of the specimens varied depending on the section selected: 4 in, 6 in, and 8 in (10 cm, 15 cm, and 20 cm). Test results revealed that beams might fail quickly due to a significant decline in yield and ultimate strength of the steel beam. The yield and ultimate flexural strength of steel beams of various sizes were dramatically lowered as the temperature increased (for all studied groups). This decline was up to 50%. Fire exposure also severely reduced shear strength, with a 38% drop. Furthermore, the design strength capacity could only withstand stresses at low temperatures. Under flexural and shear dominant loading, this loss in strength was seen. Furthermore, the design strength capacity can only tolerate loads at low temperatures.

2.2.Reinforced Concrete Beam-Slab Assemblages.

Through one field study, Kodur et al. [18] conducted fire tolerance experiments on two reinforced concrete specimens in the form of beam-slab assemblies with full-scale dimensions, in addition to another two reinforced concrete slabs of small dimensions. The four specimens were strengthened with F.R.P. The specimens were tested to evaluate the reinforcement/insulation system's thermal effectiveness without any load application. After that, the beams were tested to assess the whole reinforcement/insulation system's performance under load and fire, using a small chamber as a slab furnace in which two slabs were placed over an opening supplying heat from beneath. The beams were put over the aperture of 4.87 m (16 ft) by a 3.96 m (13 ft) chamber that served as the beam furnace. The authors also used thirty hydraulic jacks to distribute the load on the samples from above, providing small viewing ports throughout the fire test to enable observation of the exposed underside of the samples along the walls of both furnaces. Based on their results, the following conclusions were drawn:

1) For reinforced concrete beams flexurally strengthened using F.R.P. sheet reinforcement, a four-fire rating can be adopted by providing enough fire-resistant insulation, as shown in this work.

2) When the insulation thickness was 25 mm (1 inch) or higher, it was determined that the insulation remained intact for more than four hours of exposure to ASTM E119 Standard fire. The effectiveness of V.G./EI-r insulation for

FRP-reinforced reinforced concrete systems was demonstrated.

3) Slabs with an insulation thickness of 38 mm [1.5 in] met the standards for a four-hour fire rating.

4) Slabs with an insulation thickness of 19 mm [0.75 in] met the fire-retardant standards for two hours.

Wu and Zhang [19] analyzed a beam-slab assemblage using data from a full-scale reinforced concrete structure, as shown in Fig. 8(a). From Fig. 8(b), the authors extracted slabs B1 and B2 and beam A.B. from the third floor and considered them a beam-slab assembly.

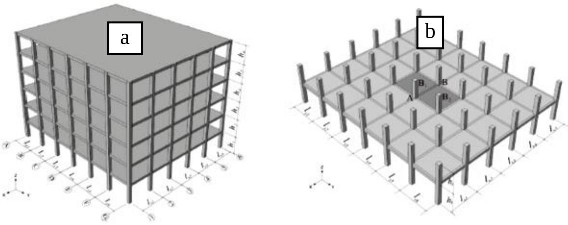


Fig. 8 The full-scale reinforced concrete structural frame of the multi-story building considered by Bo Wu and Rujia Zhang 2017 [19]. (a) the whole frame, (b) the third floor.

In their (finite element modeling), Wu and Zhang [19] exposed the beam-slab assembly's lower surface to fire while maintaining the temperature of the remaining parts at room temperature. It was noticed that, as anticipated, the surrounding components posed severe limitations when the assembly started to distort due to fire. Based on their numerical results, the researchers summarized the following concluding remarks:

1) It is essential to consider the contribution of adjacent beams connected to and perpendicular to the specific fire exposure beam to determine the rotational limitation stiffness at the end of the beam more accurately.

2) At the beam end, the rotational restriction stiffness ranged from 1.3 to 20.9.

3) As plate thickness and the sectional size of the beam increased, the stiffness of the distributed rotation limitation in the middle of the plate's edge also increased. In comparison, the stiffness of the restriction reduced as beam length increased.

4) It was suggested that a rebound formula for determining the stiffness of the distributed rotation restriction at the edge of the slab generally agreed with their numerical results.

3.BEHAVIOR OF REINFORCED CONCRETE SLABS EXPOSED TO FIRE

3.1 General

Fire-loaded reinforced concrete slabs were studied by many researchers [20-22]. Bailey and Toh [23] evaluated 26 small-sized slabs in a subsequent test at room temperature and 22 small slabs at high temperatures. The goal was to directly compare failure patterns by performing similar tests at ambient and elevated temperatures, as shown in Fig. 9. Different reinforcement ratios were obtained using five types of mesh mild steel and six types of 1.4301 (304) austenitic stainless steel. It was concluded that compression failure and further increases in the boost ratio resulted in minor improvement. In contrast, an increase in the percentage of reinforcement resulted in improvement, "which indicates the membrane workload defined as the maximum continuous load divided by theoretical yield load". It was also concluded that for some vertical displacement, square slabs performed better than rectangular slabs. Even though both slabs had the shortest spans of 1.1 m, the square slabs collapsed at a lower vertical displacement than the rectangular slabs, Fig. 10. It is well known that increasing the temperature reduces the slab's resistance to fire. The reduction occurred because exposure concrete to heat leads to physical and chemical changes such as a dry environment, aggregate decomposition, and cement paste drying. These modifications increase pore pressure through internal microcracks, water evaporation, and concrete deterioration [24]. Additionally, the steel reinforcement's yield strength declines as the temperature rises. Under high temperatures, concrete spalling is the main reason for decreasing fire resistance [25, 26]. The behavior of concrete slabs under fire is highly sensitive to the stiffness and ends restrain condition. Surrounding structures offer compressive restraint that decreases the thermal expansion of slabs. As a result, unrestrained one-way slabs generally have less fire resistance than restrained slabs [27-29]. Codes of application declare that the degradation of strength in either concrete or steel reinforcement occurs because temperature rise depending on the aggregate nature and the type of steel [30,31]. However, these codes claim that the strength deterioration is mainly due to the temperature of steel reinforcement. In the state of slabs, Eurocode2-2004 [30] grants a temperature allocation outline over the slab depth or the cross-section of the beams and columns' state. These outlines depend on the fire resistance grade when the load-bearing extends to 30 or 60 minutes in standard fire exposure. It provides simple arithmetic procedures to calculate the mechanical behavior at 500 °C. The committee of ACI-216 [31] considered the slab's fire resistance based on the slab's relative bending capacity," which is the ratio of the moment due to the applied load to the moment capacity of the section", where the thickness of the cover depended on the aggregate type. The ECP 203-2007 [32] considered fireproof for various structural members, "slabs, beams, and columns", depending on the dimensions and the concrete cover thickness.

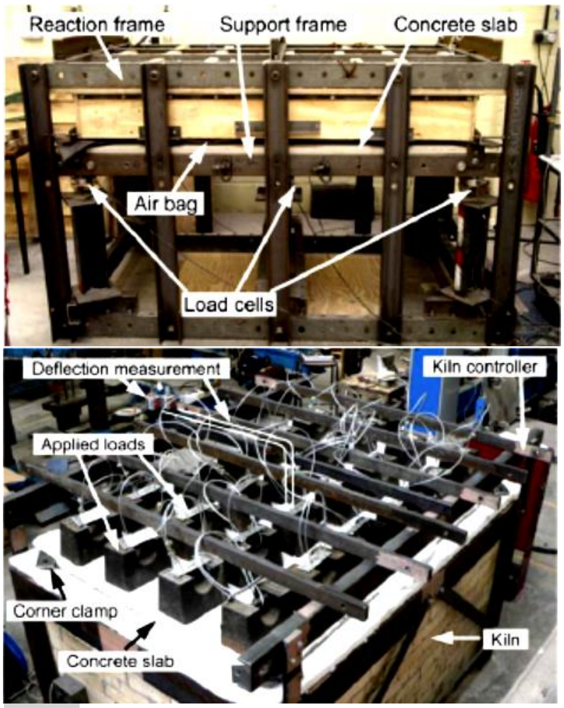
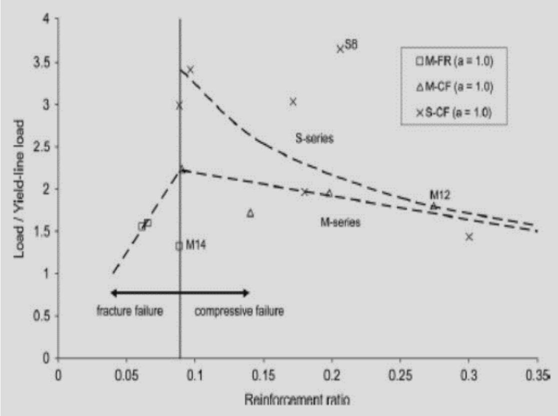
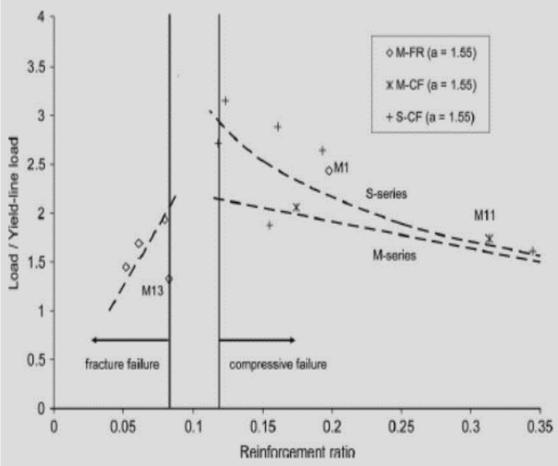


Fig. 9 Ambient and elevated temperature tests [23].



(a) Square slabs



(b) rectangular slabs

Fig. 10 The enhancement–reinforcement ratio relationship for square and rectangular slabs [23].

3.2.One-Way Reinforced Concrete Slabs

With support from a multitude of test data from the Portland Cement Association, the analysis of the reinforced concrete slab was carried out by the analysis methodologies used in room temperature concrete suited for fire resistance assessments. The behavior of simply supported reinforced concrete slabs exposed to fire from the bottom face is illustrated in Fig. 11 [33].

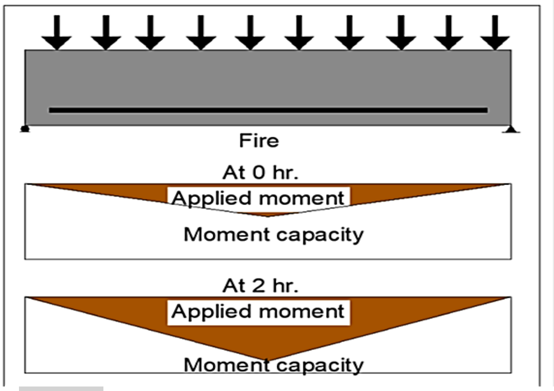


Fig. 11 Effect of Fire on Resistance of Simply Supported Reinforced Concrete Slab [33].

The ends of the slabs rotate freely, and the slab also is freely elongated (not thermally restricted). Reinforcements consist of straight bars placed near the bottom of the slab. Since the bottom face of the slab was exposed to fire, it expanded more than the top, and subsequent bending made the slab deflect down. Additionally, as the temperature rose, the concrete and the reinforcing, which were close to the bottom face of the slab, strength decreased. If the strength of the reinforcement dropped below that required to support the slabs and any overlapping load, bending failure would occur [33]. The most significant part of the research effort in the literature dealt with the fire resistance of reinforced concrete slabs during exposure to fire. However, a few works have been conducted to study the influence of cooling time on concrete slabs' fire resistance. These studies considered only the cooling initiation time on fire resistance [19,21,24]. However, to the authors' knowledge, no research efforts have addressed the dangers of the time of cooling on the resistance of fire. There is a tough time between the cooling start and fire resistance. This challenging time fails the concrete slab if it is cooled before it can resist fire due to the fire extinguishing (cooled) while the temperature in the core of the concrete slab is still increasing. Allam et al. [34] Offered a finite difference approach to track the fire response of one-way reinforced concrete with simply supported slabs according to the criteria of ISO834 Fire. The "thickness of the concrete cover, presence of plaster at the exposed surface, and the ratio of live load" was a few factors considered. By comparing the predicted temperatures to the actual ones, as illustrated in the graph, the pattern is verified against experimental and numerical data, Fig. 12. The pattern can anticipate the cooling effect and the fire resistance before the latter (time). This study found that the yield strength of the reinforcement decreased with the increase in the reinforcement temperature, so the section capacitance decreased, Figs. (13- 15), increasing the thickness of the concrete cover resulted in an almost linear increase in fire resistance, Fig. 16, the presence of plaster significantly increased the slab's fire resistance, and its effect was more evident in the slabs of a thin cover of concrete than in the slabs of a thicker cover of concrete, where a 162% increase in fire resistance was achieved in the case of the 15 mm cover compared to 102% achieved in the case of the 30 mm cover, Fig. 17. The higher the live load, the more significant the drop in fire resistance which was almost consistently in all cases by around 28%.

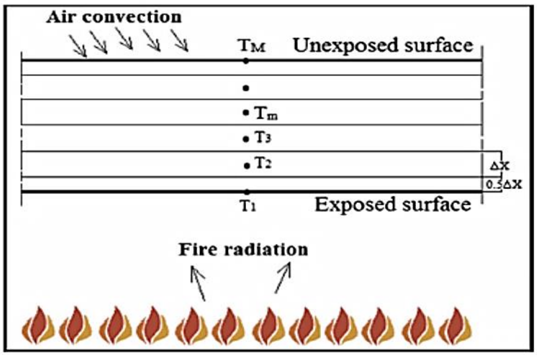


Fig. 12 Heat transfer Model [34].

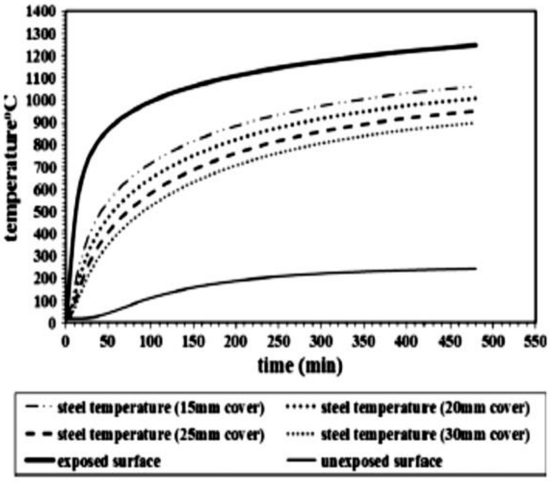


Fig. 13 Temperature distribution for concrete slab surfaces and steel (without plaster) [34].

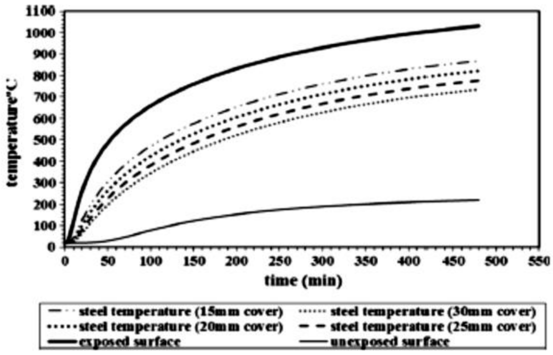


Fig. 14 Temperature distribution for concrete slab surfaces and steel (with plaster) [34].

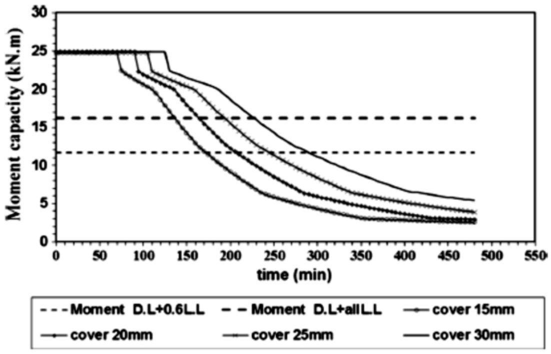


Fig. 15 Moment capacity degrading for different concrete covers (with plaster) [34].

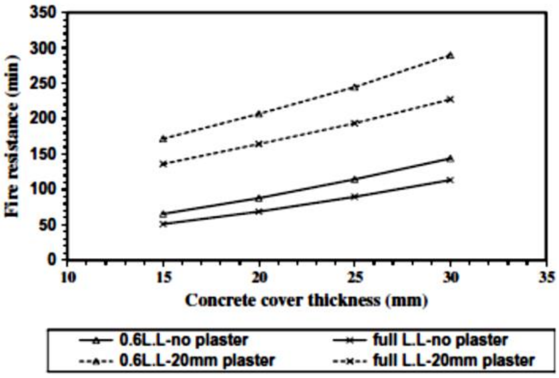


Fig. 16 Variation of concrete slab fire resistance with different concrete cover thicknesses [34].

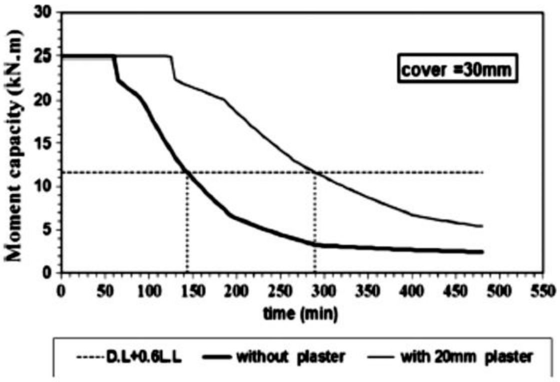


Fig. 17 Effect of live load ratio on the moment capacity degradation of slabs with concrete cover 15 and 30 mm [34].

Prasad [35] examined the thermal behavior of reinforced concrete slabs exposed to fire. The study focused on the percentage deflection of a reinforced concrete slab when subjected to higher temperatures. Reinforced concrete slabs (3300x1200x200 mm) with concrete grades M25, M70, and M100 and cover thicknesses of 30mm, 40mm, and 50mm were designed utilizing ANSYS14.5 to show the behavior of the slab at increasing temperatures. A pressure of 0.1N/mm2 examination was conducted to evaluate the load-deflection pattern and the deflection percentage without and with heat. In the first step, nine examples were modeled to show the effect of different grades of concrete with varied covers. The ISO 834 curve was used to apply heat. The results indicated that when the cover given increased, slab deflection decreased. It was also revealed that when the concrete grade increased, the slab deflection decreased. Based on the findings, the study found a minor deflection for M100 with a 50mm cover. Abdullah and Al-Khazraji [36] developed a plan for six simply supported, highly reinforced, one-way concrete slabs with reciprocally interwoven steel bars. The bending notches for the static test were placed in the middle third of the bottom face of the slabs because excessive deflection and yield of the steel tension bars were predicted to cause bending failures for all samples (constant moment). Nearly no spalling appeared in the cover, and the distribution of cracks on the slab's surface was determined by burning the samples. The deflection history of the burned samples also showed that the deflection decreased in the second hour. The failure load, plasticity factor, final deflection, and service deflection of samples rose when the binding ratio of burnt and unburned samples increased. The bonded steel bars limited the tensile reinforcement for strain in the strain-hardening zone, which improved the load-strain curves; however, the strain of concrete for the compressive face rose nonlinearly versus the load until the slab collapsed. The compressive strength of concrete was reduced after exposure to fire flame, and the residual compressive strength was about (57.5%) in the case of 500 °C burning and sudden cooling. A load of failure was also reduced by (28.7%), although the ultimate deviation rose by (14.41%).

3.3.Two-Way Reinforced Concrete Slabs

In their two works [37-38], Bailey and Moore devised a method for determining slabs' maximum load-carrying capacity, including tensile membrane reinforcement effects at elevated temperatures. When using this technique, a crack in the center of the slab was regarded as a failure mode. The failure mode described by earlier researchers [39, 40] involved the formation of full-depth cracks at the intersection of the yield lines. Linus [41] provided a fire resistance test report for six concrete slabs using fire BRANZ. The slabs were horizontally unrestrained, with four edges simply supported. The slabs were subjected to a constant distributed load. At the same time, the slabs were heated from the bottom beyond a furnace. The mesh bar's spacing effect on the slabs' deformation ability was evaluated. According to fire tests, the closer bar spacing and higher steel content prevented the development of vast and deep cracks, allowing the slabs to maintain their reliability rating. Due to the significant increase in steel's ductility at high temperatures, the cold-drawn mesh used in the tests functioned well and did not burst. The tests also demonstrated the critical role of the tensile membrane work in preserving the floor slabs' structural integrity under fire circumstances by significantly supporting the loads above the anticipated yield line capabilities. Next, Lim et al. [42] presented a paper that studied the fire behavior of two-way reinforced concrete slabs by a particular purpose Nonlinear Finite Element Program, SAFIR. Modeling results agreed with fire tests and showed that the membrane action of two-way reinforced concrete slabs could be predicted under fire conditions using the SAFIR shell element. It was concluded that if the two-way slabs deformed in double curvature and developed tensile membrane action, they would have excellent fire resistance. A numerical work described by Moss et al. [43] consisted of modeling fire behavior for two-way reinforced concrete slabs in a multi-story multi-bay building Fig.18. The structure around the perimeter with no internal beams and four internal columns supporting the concrete slab. The nine bays of the concrete slab were all on the same level and open to the elements. The authors utilized two fires. The first was borderline fire based on an ISO834 one-hour fire that degraded to ambient temperatures for another two hours, and the other was an ISO834 normal fire lasting four hours. If there was no decay phase during a fire, the findings demonstrated that the value of the membrane tensile forces was affected by both the loss of strength in the reinforcing bars upon heating and the increase in vertical deflections. However, after being exposed to fire for four hours, failure did not occur due to the positive effects of large displacements and tensile membrane action. The slabs responded differently in fires with decay because of the increased strength and ongoing thermal contraction that cause the membrane forces to stay tight and keep growing long after the fire has been started. Throughout the four hours of continuous exposure to fire, these membrane forces increase far beyond what was anticipated. To resist membrane tensile pressures, designers must ensure that all reinforcing slabs, particularly upper steel, are correctly fixed in the edge beams. According to several failure criteria; such as the aggregate type, slab thickness, concrete cover, fire load, the surface area of exposure, and end-restraint conditions on two-way slabs; many two-way slabs were constructed [44] to measure the influence of various parameters and their impact on fire rating, Fig. 19. The study demonstrated that the fire ratings of more giant thickness slabs were unconventionally planned, however, those of Eurocode 2 (2004) was. When carbonate aggregate was replaced with siliceous aggregate, the fire rate rose by 15%. The fire rate increase indicated that the thermal properties of the different types of aggregates varied and had a variable impact on fire resistance, Fig. 20. According to the study, fire resistance increased as slab thickness and cover increased. However, because the cover of the reinforced concrete slab was restricted, extending it to boost fire resistance was impossible. The slabs were exposed to intense fire, and when exposed to fire from the top and bottom sides, their fire resistance dropped by around 40%.

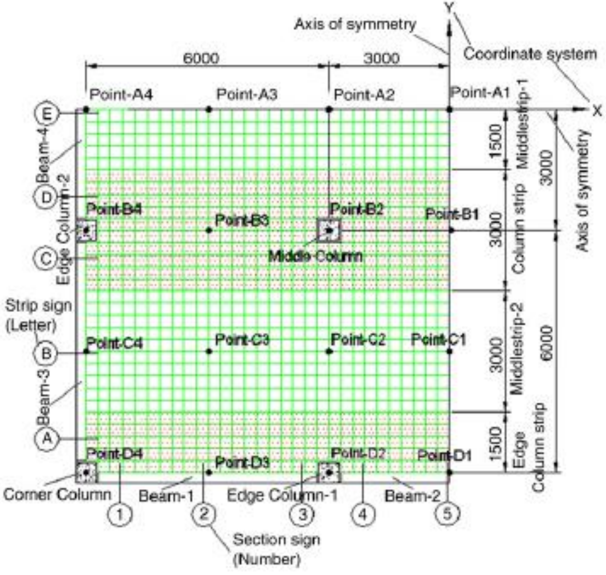


Fig. 18 Reference diagram for the nine-bay flat slab (showing one-quarter of the slab [43].

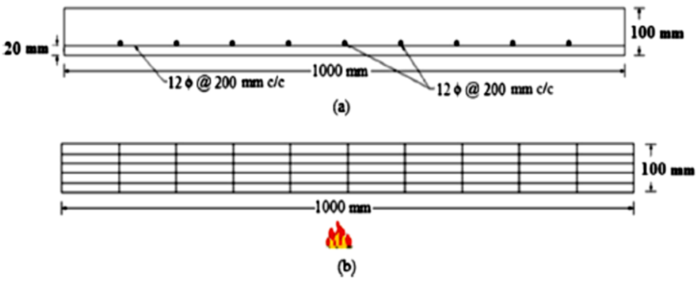


Fig. 19 Geometric and discretization models for numerical analysis [44].

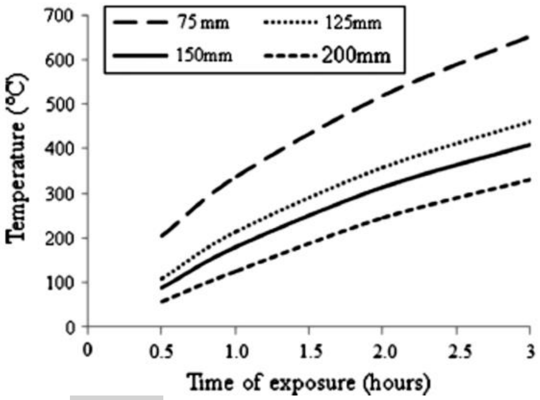
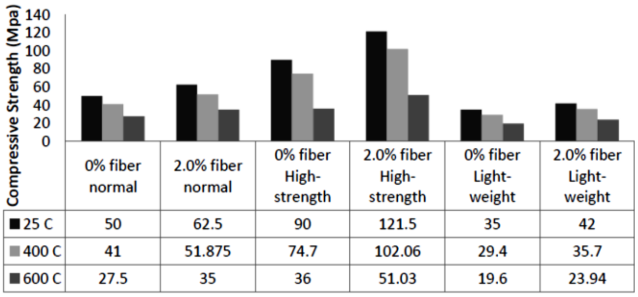


Fig. 20 Temperature time distribution at various depths of carbonate and siliceous aggregate reinforced concrete slabs [44].

Ghanem et al. [45] investigated the behavior of reinforced concrete slabs subjected to fire. The analysis was performed in two stages. The fire duration in the first stage (group A) was variable and ranged between (1 and 3) hours. However, the concrete cover was set and equal to 25 mm. In the following phase (group B), the concrete cover varied from 30mm to 35mm and 40mm, but the fire duration remained constant at 4 hours. The structure's reactions were determined by the fire length and the concrete cover's thickness. The R.C. (3100x3100 mm) slabs were modeled to demonstrate the impacts of slab thickness and varied fire durations. The deflection, lower strain, and higher strain of a reinforced concrete slab at 600 °C were also measured for the two phases. The results revealed that the failure load during the first phase (group A) decreased from 15.3% to 36.6% compared to the control slab. Compared to the reference slab, the failure load in the second phase (group B) decreased from 10.22% to 21.9%. Also, the failure load increased by 22.22% when the concrete cover was increased from 25 mm to 35 mm and burnt for a consistent time (4 hours) while maintaining the same temperature. Later, an experimental program based on 18 reduced scales reinforced concrete slab samples, which were simply supported, was designed and put into place to examine the bidirectional slab behavior [46]. The software offered different mixes: N.S.C., H.S.C., and L.W.C., with corresponding compressive strengths of 50, 90, and 36 MPa. After being cured for 28 days, all samples were left in the lab for seven days. Then the samples were heated in an electric oven at various temperatures, Fig. 21. The study's findings indicated that exposure to high temperatures reduced the concrete strength of all types of concrete, including regular strength, high strength, and lightweight concrete.

Fig. 21 Oven used for heating samples [46].

The use of steel fibers improved the resistance behavior and permitted larger forces. The strength of the concrete had a significant impact on the cracking load. The final load was marginally raised by the steel fibers' effect when the slabs were exposed to high temperatures. However, the same negligible effect was shown as the temperatures rose in the slab samples without steel fibers, Fig. 22.



	0% fiber normal	2.0% fiber normal	0% fiber High-strength	2.0% fiber High-strength	0% fiber Light-weight	2.0% fiber Light-weight
■ 25 C	50	62.5	90	121.5	35	42
■ 400 C	41	51.875	74.7	102.06	29.4	35.7
■ 600 C	27.5	35	36	51.03	19.6	23.94

Fig. 22 Effect of steel fiber on the ultimate load capacity of slabs Temperature (25, 400, and 600 °C) [46].

4. A SUMMARY OF THE IMPORTANT PARAMETERS IN THIS REVIEW

From previous reviews, the following summary can be simulated:

Influence of Parameters on Structural Elements Fire Resistance

Bottom Concrete cover	Lateral Concrete cover	Time exposure	Type of aggregate	Type of concrete
Increasing the thickness of the bottom concrete cover improved the fire resistance of the elements [5, 7, 10, 31, 33, and 34].	Had an insignificant practical effect on fire resistance [5].	Increasing the exposure time when the heating temperature had low enhanced the effect on strength [8,9].	The degradation of strength depended on the aggregate nature and the type of steel [29,30].	High temperatures reduced the strength of all types of concrete [45].

5.CONCLUSIONS

In concrete, the increase in temperature is the cause of changing the free water from liquid status to gasiform status. As a result of this state of transformation, variations occur in the average heat transfer from the concrete ingredient surface to its inside. The strength and modulus of elasticity in both reinforcing steel and concrete decrease with the increase in temperature. However, the rate of strength and modulus reduction depends on the increased firing temperature rate and concrete insulating features. Knowing that concrete is not a burning material. According to tests or methods based on tests, the fire-resistance rating is the amount of time (typically expressed in hours) for which a building element (a structural member), component, or assembly maintains the ability to confine a fire, continues to perform a specific structural function, or both. In general, it was discovered from earlier investigations that the fire reduced the ultimate loads of structural parts. Additionally, the deformation caused by the fire was worse. The findings show that the temperature distributions rise with the increase in load level, which is consistent with the fracture diffusion. However, when the cross-section increases, the maximum beam deflection during the fire test nonlinearly reduces. The elasticity and hardness decrease with increased stress or the duration of time exposed to fire. An increase in the cross-sectional area of the beams increases their flexibility and stiffness. The thickness of the concrete in the beams and slabs boosts the structure's fire resistance. The load ratio reduces the column's and the beam's fire resistance but has an almost insignificant impact on the slab's deflection. Additionally, the column's fire resistance is dramatically reduced while the beam's fire resistance increases due to the axial restraint. The circumstances above could endanger life and property and impact the behavior and performance of R.C. elements. Therefore, individual evaluations of each structural element's behavior must be recognized to ensure optimal design.

The results of the slabs' investigations concluded that:

1- The bottom of the slab's concrete and the reinforcing steel heat up faster than the top of the steel and the surface of the concrete. According to boundary conditions, the thermal gradient resulting in the slab tries to generate thermal bowing but cannot do so, leading to a significant redistribution of bending moments.

2- As the temperature of the bottom steel crosses 300 °C, the yield strength of the steel falls with rising temperature, causing the concrete section's negative (sagging) bending strength to decline as well as its membrane strength. When the bottom steel hits 300–400 °C, the bending moments in the slab reach their maximum, and as the bars continue to heat up, the slab loses strength.

3- The heat-induced loss of strength in the reinforcing bars and rising vertical deflections serve as barriers to the tensile membrane forces.

4- The bottom of the concrete slab starts to cool once the temperatures drop. As a result, the yield strength of the bottom reinforcing increases and starts to contract, along with the lower part of the slab.

5-After the fire is extinguished, the vertical deflections cease to grow.

6- As the slab cools and the temperature gradients lessen, the average bending moments turn positive to negative.

7-Due to increased strength and ongoing thermal contraction, the membrane forces turn tensile and continue to rise even after the fire has been put out. During the continuous four hours of fire exposure, these membrane forces increase far beyond what was anticipated. To withstand the tensile membrane stresses, designers must ensure that all slab reinforcement, particularly the top steel, is adequately anchored into the edge beams.

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