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Prestressed hollow-core slabs performance at high temperatures- A review

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Abstract

Pre-stressed concrete hollow core slabs (HCS) are now progressively used in commercial, industrial, and residential buildings due to their sustainability, affordability, and adaptability. The performance of HCS units subjected to fire is particularly difficult and is attributable to their unusual cross-section, which features voids. Numerous investigations were executed on HCS at high temperatures concerning the crucial temperature and failure mechanisms of both concrete and prestressing steel. Fire performance is influenced by a number of variables, including support condition, concrete aggregate type, slab thickness, fire insulation and cover thickness for reinforcement, spalling accessibility, void cores and size, and firing methodology. While a number of these variables have received extensive research, some have been noted as potential contributory reasons for failure, while others have received relatively little attention. This paper summarises numerous experimental, numerical, and analytical studies about the attitude of HCS vulnerable to fire in addition the building standards limitations to provide a valuable reference for future researchers.

Keywords: Pre-stressed, hollow core slabs, fire resistance, spalling.

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1. Introduction

Prestressed hollow-core provide a number of advantages over reinforced concrete systems; quick construction, architectural aesthetics, efficient use of space, and low maintenance costs. They are also more sustainable because they are extremely durable, with an exceptional lifespan due to their resistance to corrosion and cracking. Furthermore, producing HCS in a controlled factory environment reduces waste, noise, and emissions. HCS is depicted in Figure 1.

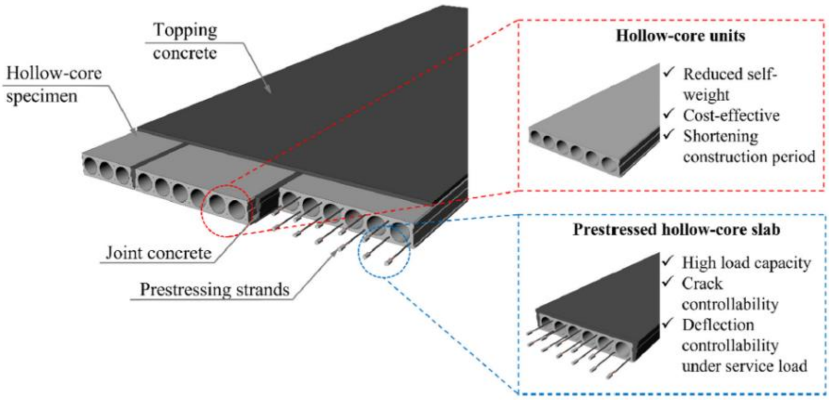


Figure 1. Prestressed hollow-core slabs [1]

The performance of HCS units vulnerable to fire is particularly difficult and is attributable to the unusual cross-section (CS) featuring voids. HSC display substantial compressive stresses in the flanges, whereas tensile stresses (F_t) occur in the web which might surpass the F_t capacity of concrete, arising in premature shear failure of HSC susceptible to fire.

The fire behaviour of prestressed HSC is influenced by a number of variables, including support condition, concrete aggregate type, slab thickness, fire insulation, cover thickness for reinforcement, spalling accessibility, void core arrangement and size, and firing methodology. Although some of these features have attracted extensive research, others have received relatively little attention. This paper provides a comprehensive study of prior experimental, numerical, and analytical surveys concerning HCS in the presence of fire, which will become an outstanding reference for future researchers.

2. Experimental Studies on HCS

Over the previous four decades, more than one hundred HCS units were experimentally evaluated when subjected to typical fire circumstances [2–16, 19,53]. The fire was by using ISO 834 [3- 15, 25] fire or ASTM119 [2, 19]. The bulk of these experiments were intended mainly to measure the fire resistance (FR) of separate HCS units instead of the structural attitude of the HCS system under temperature. This section provides a comprehensive review of previous experimental research for HCS under fire.

2.1. Support condition

Multiple studies have been carried out concerning the effects of support conditions (restrained and unrestrained) on HSC behaviour against fire [3, 6, 8, 11, 12, 13]. The fundamental rule is, without a doubt, thermal expansion. Restrained supports exhibit dramatically increased cracks under fire due to restrained thermal expansion, whereas free supports exhibit the opposite. Borgogno (1997) examined the mechanisms of failure of HCS concerning rigid supports. Regarding fire attitude, bending, anchoring, shear compression, and shear tension failures were recorded. The findings show that support conditions had a significant impact on the structural behaviour of HCS [3].

Similar trends were discovered by Van Acker (2003) with regard to nearby structures; the investigation was performed by using three supporting beams; one to four 12 mm-diameter bars were used to affix the modules to the exterior and interior support beams. It was discovered that bending failure occurred in 7/8 cases at loads that were 1.78 to 3.24 times superior to the serviceability live load, with 2.72 being the average load factor [6].

Inadequate knowledge of overall structural performance is the major flaw in the majority of national and international design laws governing fire safety in buildings. Therefore, rather than the loss of strength at high temperatures, the fire endurance may be controlled indirectly by thermal expansion that is limited by edge columns through the supporting beams [6].

Van Acker (2003) concluded that shear stresses of 0.25 to 0.40 N/mm^2 may be imparted through the longitudinal joints. These longitudinal pressures are then distributed across the whole neighbouring floor, and the reinforcement in HCS is not vulnerable to fire [6]. Figures 2 demonstrate the effect of neighbouring structures on the longitudinal expansion.

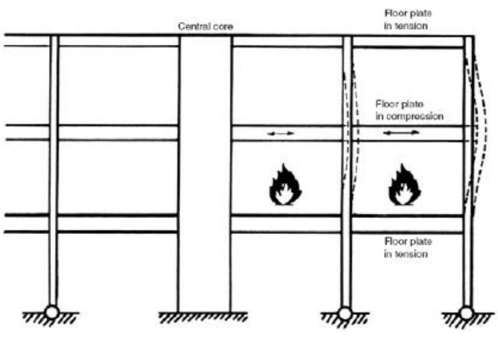


Figure 2.a: Elevation demonstrates blocking impact of the edge construction

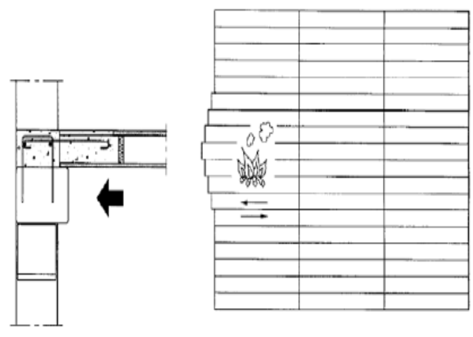


Figure2.b: Neighbouring units obstructing longitudinal expansion

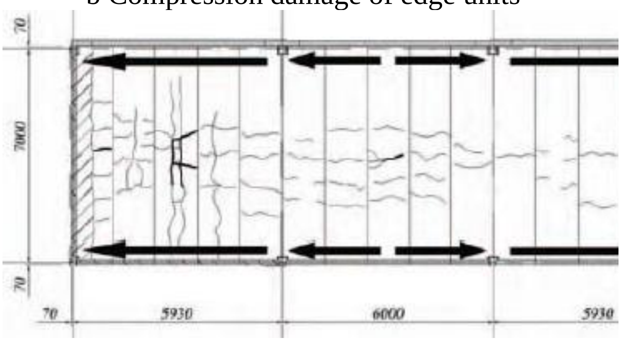
Figures 2. The effect of neighbouring structures on the longitudinal expansion [6].

Limited research was conducted on the supporting conditions of HCS in real structures. Indirect actions have an impact on the fire destruction of concrete structures. resulting from thermal expansion rather than material loss at severe temperatures, which might be regulated by edge columns via the supporting beams [11, 13].

Bailey et al. (2008) investigated 2 full-scale tests, which were conducted on 15 HCS with very intense fires supported by protective steel construction. The fire compartment measured 7020 x 17760 x 3600 mm. The joints between the units were filled with grout. The only variation among the two tests was the end restraint conditions for HCS. In the first test, the units were grooved all around the columns, and slabs were placed directly on the supporting beams. Grout made of C25/30 concrete was used to fill the joints between the HCS and the spaces between the columns and the HCS. During the second test, T12-U bars were positioned in the centers, and a shear stud with a diameter of 19 mm was fastened to the steel beam. Grout filled the spaces between units and steel columns, the cores containing the rebars, and slab ends. Cracking was observed at the centre edge of the column, highlighting that the column was pulled out rather than the units. Test results demonstrated that the steel frame doesn’t constrain the units' longitudinal thermal expansion, but because there was no shear failure during the test, it is conceivable that another load-path process was taking place. Additionally, it was noted that a lateral compressive strip formed at the units' ends due to resistance to thermal expansion. Depending on this study, it was found that the compressive strip behaves favourably by raising the unit flexural and shear capacities [11]. Figure 3 clarifies the effect of HCS restraint on its failure.

a Cracking around internal edge column

b Compression damage of edge units

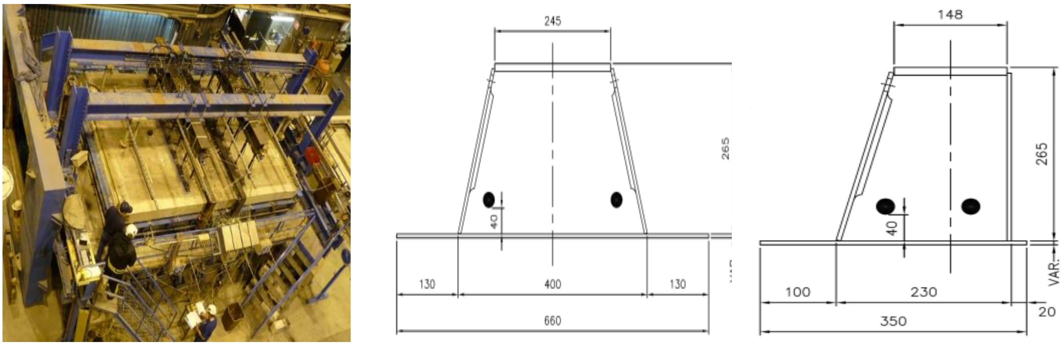


c Slabs restraint creates a compressive strip

Figure 3: The impact of HCS restrain on its failure [11]

Peltonen S. and Plum C. M. (2010) assessed the potential effect of using Peik Delta Beams (DB) to support the HCS during fire conditions. They presented the outcomes of four fire experiments on HCS supported by DB without insulation. The investigation parameters were the duration of the fire, the duration of the cooling period, and the loading in four tests, which varied. [13].

None of the specimens failed the test at any point. The greatest fire-induced deflection was 82 and 75 mm for the slab and the DB, respectively, for the 60-minute test, and 145 mm and 110 mm, respectively, for the 120-minute test. According to the investigation, DB could transfer the load from HCS to its inclined web but not over its bottom flange support. At different depths in the HCS, temperature profiles were produced. The study presents solid test results on how HCS behaves during a fire when combined with other constructions, in this example, DB. The study focuses on the private DB and withholds information on the precise HCS activity [13]. Figure 4 illustrates the test arrangement and the cross section (CS) of the DB [13].



a. Test arrangement b. CS of main DB c. CS of edge DB

Figure 4: Test arrangement CS of the DB [13]

M. Shakya and V.K.R. Kodur (2015) investigated six HCS, each 1200 x 4000 x 200 mm, with six cores and seven prestressing strands. with a diameter of 150 mm and a 25 mm-thick bottom layer of concrete. The strands were covered in 44 mm of concrete. The central piece of two full-scale HCS, measuring 2.44 m out of 3.65 m, was set on fire. Five HCS were tested with just basic support, allowing the slabs at the ends to spin freely. Due to the preventive support conditions, one slab's longitudinal/axial movement was restricted during testing. The findings of the fire experiments clarified that HCS can sustain service loads under specified and typical fire conditions for a minimum of two hours. Prestressed HCS fire performance is significantly influenced by the fire situation and load level, HCS performs better in designed fire scenarios than in typical fire situations. Axial constraint conditions at supports have a big impact on how HCS reacts to fire, and they can increase the FR of conventional HCS by roughly 30 minutes. Figure 5 illustrates failure modes in HCS under fire exposure [19].

According to the research listed above, the support condition has a significant impact on HCS FR. High temperatures are known to cause strains in concrete structures of the same order of magnitude as dead and live loads on some occasions. However, temperature-related stresses are created only when thermal expansion or contraction is restricted; the problem is exacerbated when a portion of the roof slab is exposed to fire.

In general, the expansion of structural parts caused by heating is frequently limited by other building components that are either permanent or part of the exposed element. For instance, the colder areas of a continuous concrete slab as well as the connecting columns and beams limit the expansion of the slab when heated. The two forms of known constraint are axial and angular. Axial constraint prevents elongation, whereas angular restraint opposes the bending or rotation of an element. Both forms of constraint may be partial or total (concrete construction), and so they can be applied either inside (concrete construction) or outward to an element.

Typically, quantifying the extent of constraint is difficult, especially when HSC are subjected to fire conditions. Some of the issues affecting its estimation include the deformation of the restricting element, the variety of factors for thermal expansion, the variation of elastic moduli with temperature, shrinkage due to drying, and creep. Restraint is indicated quantitatively by either stating the pressures operating on the constrained structure when expansion is prohibited or by measuring allowable movement [50]. Additionally, variations in constraint conditions have a major impact on the FR of HCS. The FR of concrete projects attributable to constraint is typically lower than that of steel because excess compressive stresses are formed, which may lead to cracking, spalling, buckling, or collapse.

In terms of FR, however, restraint is not always the worst decision in HCS. Structural fire performance is improved when horizontal members are restrained. The capacity of axially or angularly restrained slabs subjected to fire, for instance, will develop since the bottom of the slab continues to be heated more than the top, causing larger restraining pressures there. The additional restraining forces result in a moment that balances the applied moment, increasing the moment capacity.

Contrary, if a HSC's topside is heated, the compressive pressures in the compression zone will rise, which lowers fire resistance. When buildings are heated, concern should constantly be directed to the columns and walls since they often lose their fire resistance due to higher lateral displacement and eccentricity. On the other hand, if an eccentrically loaded column is heated on either its tension or compression side, it will undergo the same impacts as those for horizontal members, with heating on the tension side leading to an increase in capacity and heating on the compression side resulting in a decrease in capacity.

In reality, the HCS voids partially inhibit the temperature transmission of heat from the bottom to the top of the slab or the reverse, depending on heat direction; the heat transition is achieved through the slab's webs. This phenomenon is caused by the enormous difference in thermal conductivity between concrete and air, which is 1.7 and 0.03 W/mK, respectively [51]. The HCS voids are generally good insulators in the absence of convection. Consequently, many insulating materials function simply by having a large number of gas-filled pockets, which prevent large-scale convection. As a result, HCS are thought to have a higher FR than solid slabs.

2.2. **Spalling *accessibility***

Fire Spalling is among the major problems affecting concrete construction. The free and associated water in concrete starts to evaporate during a fire, creating pore pressure that produces strain on the inner parts of concrete structures. As soon as the fire remains, the generated stresses develop progressively to a value that exceeds the strength of the concrete ft and subsequently, little bits and occasionally considerable parts fall out of the concrete surface; this is characterised as spalling [14]. Spalling is the process of tiny scales and occasionally larger pieces breaking off the concrete surface when the produced stresses reach a limit that exceeds the ft of the concrete even after the fire has been extinguished [14]. As a result, fire may spread quickly to concrete cores, increasing pore pressure and internal stresses that significantly reduce concrete strength as well as the stiffness and strength of the reinforcing [15]. These negative impacts will significantly impair the bonding between concrete and reinforcement [16], which will lead to differential thermal elongation between concrete and reinforcement as well as serious damage to the joints and connections between different structural parts. Spalling is essential in hollow core slabs, which lack transverse support. The capacity of concrete construction to support loads and maintain structural integrity would both be put at risk [15].

Concretes with a higher compressive strength are more prone to spalling and have a lower FR [17]. This may be explained by the lower permeability that comes with high-strength concrete. Relative humidity measurements of the moisture content in concrete specimens have an impact on the amount of spalling that has occurred. When RH rises, spalling increases and vice versa [17, 18].

Although the goal of some experiments is to measure spalling, sometimes it does not appear, as the aforementioned factors that lead to it are totally unavailable. We draw on the experience of Andersen et al. (1999), who investigated three different fire experiments on simply supported high strength concrete HCS with thicknesses of 185 mm, 220 mm, and 270 mm and dimensions of 1200 mm by 6000 mm. No topping concrete was utilized. After 10 minutes of testing, a bond failure between the primary reinforcement and the surrounding concrete was recorded. Shear failure was used to describe the failure mechanism that caused collapse in all three experiments. Comparable rupture figures were recorded for slabs with thicknesses of 185 mm and 220 mm; rupture records were extremely comparable, demonstrating a typical rupture with a rupture line of 45 degrees, and the shear failures occurred about 1 m from the support. The supporting concrete broke off at the support, resulting in shear collapse of a 27-mm-thick slab.[4].

Lennon (2003) also indicated no considerable spalling after performing two full-scale fire experiments regarding spalling of the slab and premature shear failure at the supports. With the exception of structural topping, the test settings and compartment structure were comparable. There are two distinct methods for providing this critical limitation to the floor units. The cracks in one slab were filled, and a structural topping of concrete with a 50 mm depth and mesh reinforcement was added. On the other slab, the seams above the supports were filled, and hooked reinforcing bars were installed. Despite a maximum Temp. of more than 1200 °C and a very high heating rate, the investigation came to the conclusion that spalling wasn't a worry as soon as suitable curing durations were employed. Additionally, it was established that there wasn't any confirmation of the units' premature shear failure during the testing. The precast HCS floor components also fared well in severe natural fire situations [7].

The type of aggregate is a determining factor in concrete's spalling under fire. Compared to concrete built with natural siliceous aggregate, carbonate aggregate concrete offers superior spalling resistance. Because carbonate aggregate has a significantly advanced heat capacity, that helps to prevent spalling [19, 20, 21]. Zheng W. Z. et al. (2010) recorded an excellent look at minor spalling of HCS made with calcareous aggregate; by reviewing the submitted paper on 15 simply supported PC and 9 two-span unbonded continuous HCS, it was clear that there was no dramatic spalling involved—just the fall of the concrete cover at temperatures between 200 and 500 °C; this result was expected as a result of using calcareous aggregate. Although water content has only a minor effect on spalling, spalling occurs readily when the compressive stress is greater or the ft is smaller on the surface subjected to fire and the concrete strength and water content are higher under normal conditions. Unfortunately, the study investigated only one type of aggregate, and the specimens were somewhat small and may not reflect the spalling behaviour of a full-size slab. The spalling of concrete is illustrated in Figure 6 [21].

Light-weight aggregate was shown to significantly increase the amount of spalling. This is due to the fact that lighter-weight aggregate has more free moisture, which raises the vapour pressure when exposed to fire [18]. Additionally, as compared to unloaded members, loaded high-strength concrete members spall more frequently [17, 18, 28]. In addition, loading of the structure element during fire is dramatically increased spalling [10, 28], surely the combination of spalling reasons increases the probability of the appearance of the problem, this recorded clearly by Venanzi et al. (2014) when they investigated; loaded light weight concrete HCS with moderately high strength; filled with T8 expanded clay; Each test included one panel with an applied load and one without. The slabs were 4300 x 1200 x 200mm, each slab's pre-stressing reinforcing was comprised of seven 3/8" low relaxation strands and a concrete cover of 44 mm. Additional reinforcement was added to the slabs at both ends by cutting the concrete over the cores, attaching steel stirrups, and casting concrete to cover the holes. The temperature progression inside the slabs was monitored, as well as the load bearing capacity under fire conditions.

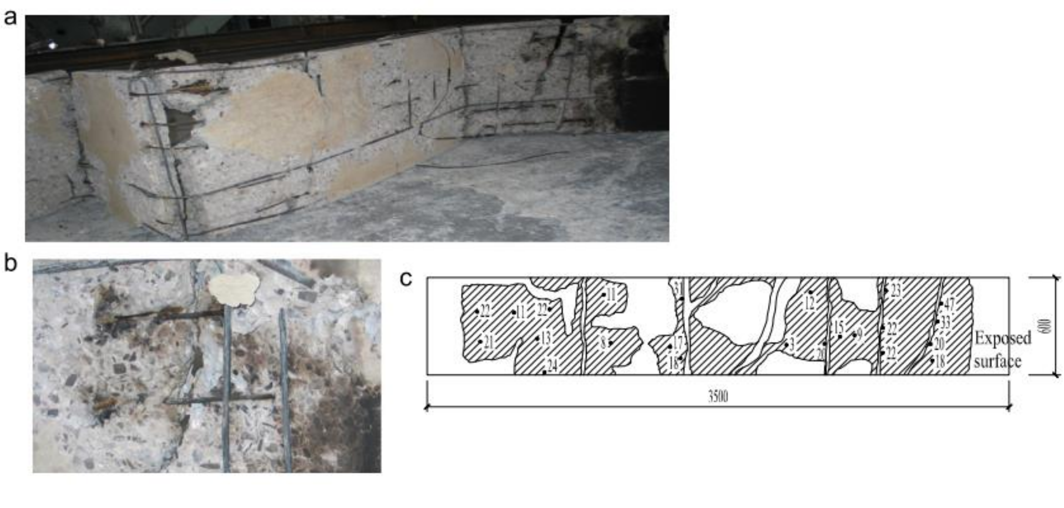


Figure 5. simply-supported slab: (a) spalling of exposed surface (b) reinforcement damage (c) concrete spalling (Spalling is shown by a hatched region, and the number there indicates the depth to which spalling may go) [21].

Another factor impacts spalling was curing; dry curing offers the lowest concrete humidit. Venanzi et al. (2014) cured HCS for many months under dry circumstances. As a result, During the first test, considerable spalling occurred in the loaded slab, but spalling did not occur during the second test, which was done on slabs that had been curing for many months under dry circumstances. After 76 minutes, the slab brittlely collapsed during the first test. It was predicted by significant cover spalling occurrences that happened at separate occasions and significantly damaged the loaded slab, as well as the creation of a pass-through vertical hole that allowed hot gases to escape to continue the test until failure, the pass-through hole was filled with insulating material on the spot. The loaded slab's significant longitudinal cracking and cover spalling resulted in section weakening and web separation at failure. Figure 7 depicts the spalling of concrete [28].

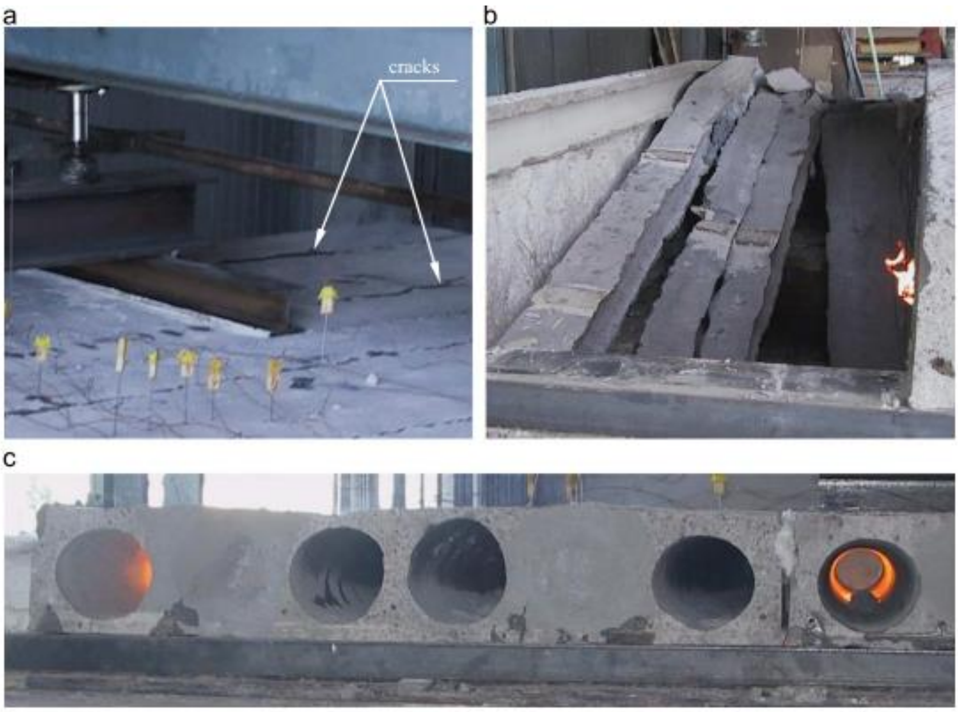


Figure 6: The spalling of concrete is occurred [28]

The difference between carbonate aggregate concrete and siliceous aggregate concrete with regard to spalling was perfectly obvious in A.M. Shakya and V.K.R. Kodur (2015) investigation; the investigation revealed that HCS produced with carbonate aggregate had a 10% larger FR than those produced with siliceous aggregate. Siliceous aggregate in concrete slabs is more vulnerable to spalling spurred on by fire than carbonate aggregate in concrete slabs. Furthermore, concrete slabs with carbonate aggregate are more prone to shear cracking. Figure 7 illustrates typical spalling in HCS under fire exposure [19].

Slab 5 (170 minutes) Slab 5 (170 minutes) Slab 6 (140 minutes)

(a) Slab 2 (20 minutes) (b) Slab 5 (120 minutes) (c) no spalling in Slab 6

Figure 7. Failure modes and typical spalling in HCS under fire exposure [19]

It is noteworthy that spalling did not correspond to the permitted deformation, this was confirmed by Inwook Heo et al. (2021); the deflection of slabs was around 27% of the permitted deformation. The study was carried out on two HCS units with depths of 200 (S1) and 265 mm (S2). The live load was applied to the tops of two slabs, S1 and S2; 1.5 kN/m^2 and 3.0 kN/m^2, respectively. The S1 sample's deflection showed a gradual increase throughout the course of the fire exposure time, peaking at 97.2 mm at 120 minutes. The maximum deflection of the S2 sample was 76.7 mm. Despite the maximum allowable deformation of the S1 sample being 360.0 mm and the S2 sample being 285.7 mm, respectively, concrete spalling was seen in both the S1 and S2 samples in the bottom half of the member exposed to the flame. The origins of the spalling were hypo-thesis to be the mobility of free water in concrete and the moisture created by the dehydration process [1].

It is obvious that there are few parametric studies committed to spalling; the majority of spalling records are merely observations on the experiment [19, 28]. Just as comparing the outcomes of multiple investigations is impossible due to the varying conditions of each experiment [1, 4, 21], Unfortunately, in previous research, the types of concrete with which the appearance of spalling spreads, such as high-strength, low-permeability concrete, were not widely used. Spalling is expected to be more widespread in loaded HCS due to the combined impact of tension force caused by loading and spalling. Similarly, restrain slabs offer highly spalling applicability.

According to the research, the majority of spalling that happens in HCS is hypo-thesis to be due to the mobility of free water in concrete and the moisture created by the dehydration process, caused by the separation of the concrete cover from the facing side due to temperature.

When the concrete cover is damaged and the strands are directly exposed to fire, the strength begins to fall drastically.

2.3. The effect of using fire insulation, increasing cover thickness and the reinforcing arrangement

Pretensioned strands are the reinforcement for HCS; the amount of stress in the strands typically determines the flexural capacity of HCS slabs. Figure 8 depicts the flexural reinforcement steel bar and strand strength at elevated temperatures [22]. The figure illustrates that at 420 MPA, the strength starts to decline dramatically; it drops by nearly 50%. Due to its decreased permeability, concrete is considered an efficient isolating material for strands. Its efficiency in this isolation is based on a variety of factors, including aggregate type, moisture content, and concrete cover.

Some research illustrates the efficiency of improving the fire isolation of strands by increasing the concrete cover [12] or using additional layers of concrete topping [1]. Furthermore, to prevent air circulation, isolate the unexposed top surface of HCS with fire-resistant materials [2] or fill HCS holes with mineral wool [10]. There has been less investigation into the reinforcing arrangement and strand axis distance on HCS fire response materials [12].

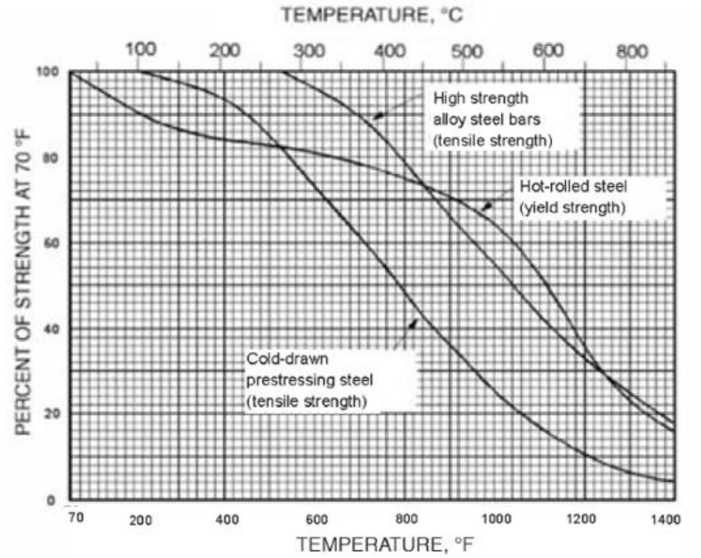


Figure 8: Strength of flexural reinforcement steel bar and strand at high temp. [22]

One of the first studies for HCS under typical fire circumstances was Abrams [2]. The purpose was to determine how roof fire insulation affected Temp increase in prestressing strands. Two HCS were vulnerable to fire testing, accompanied by 70 mm of fire insulation on the unexposed slab side. Another two slabs were verified without insulation. In the fire tests, no loading was added to HCS, and the strand temps were somewhat reduced in the insulated slab relative to slabs without insulation. This research assessed only sectioned temperatures and did not study the structural viability of HCS under fire.

However, only the test-significant correlations for unprotected HCS components exposed to ISO 834 fire were published by Schepper L. and Anderson N. E. (2000). The decks in this project are made of 220mm of pre-stressed HCS, an 80mm cast-in-situ topping of reinforced concrete, and HCS that has been partly filled with shear reinforcement. According to the visual observations, the slab bottom experienced compression failure due to a negative moment at support. Failure of components with cast-in-place reinforced concrete topping occurred after 23 minutes, and the deflection at that time was 250 mm after the fire test. Figure 9 depicts the compression failure of the slab components at the front of the furnace. [5]

Figure 9: HCS Slab failure after fire [5]

The idea of filling the hollow cores of slabs has no influence on the slab temperature; horizontal cores have poor heat exchange due to convection between the slab and the atmosphere, this was clearly demonstrated by Breccolotti M. et al. (2006). The investigation was performed for degerming the load-bearing capability for two full-scale tests using high-performance light-weight concrete. The slabs were 1200x4300x200 mm with shear reinforcements. For each test, one slab is loaded while the other is left unloaded. The holes in the first test were left open, whereas the holes in the second test were sealed with mineral wool to inhibit air flow. After 76 minutes of fire exposure, the loaded slab collapsed in shear in the first tests. In order to let the test, continue until failure, vertical pass-through holes created by spalling at the 40th minute were plugged with an insulating substance to enable the test to continue until failure. In the second test, there was no covering spalling or brittle failure. The failure time, which was 90 minutes, was in agreement with the predicted value. [10].

The effect of the reinforcing arrangement on the behaviour of the HCS structure was crucial. HCS structural behaviour is divided into two phases: initial deflection caused by thermal cracking and ultimate deflection caused by steel strength loss. The deflection is largely regulated by the reinforcing configuration [12]. Aguado J. V. et al. (2012) give vital evidence on changes in fire resistance with varied reinforcing methods. They evaluated the flexure of HCS using four different reinforcement shapes with mean axis lengths varying from 30.1 to 46.7 mm. 3/8"-diameter prestressing strands and 5-mm steel wires were utilized. The FR of HCS varied from 84 to 105 minutes. Four forms of cracking were identified during the bending test, including thermal, flexural, splitting, and longitudinal cracking [12]. Non-prestressed wires demonstrated excellent performance without failure. Strand axis distance does not seem to have much of an effect [12]. Figure 10 illustrates the CS and reinforcement arrangement of tested HCS slabs, whereas Figures 11 and 12 illustrate the cracking type and the crack pattern, respectively.

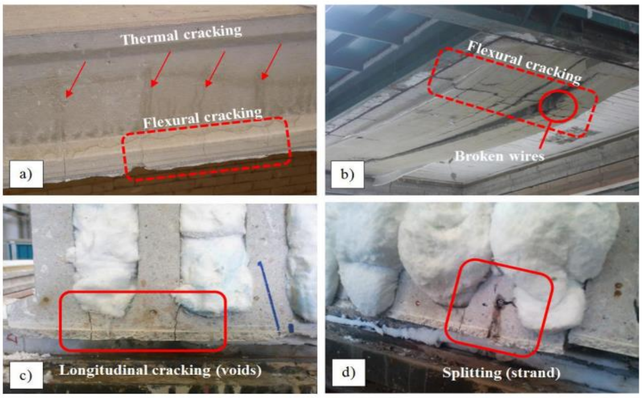


Figure 11: the cracking type
a. Cracking type b. Flexural cracking
c. longitudonal cracks d. splitting arroud strands [12]

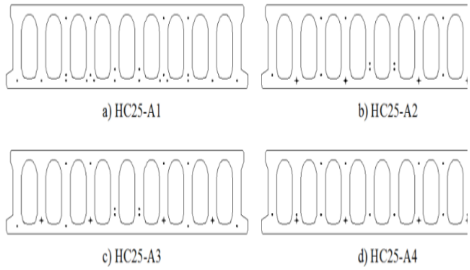


Figure 10: CS and reinforcement arrangement of tested HCS slabs [12]

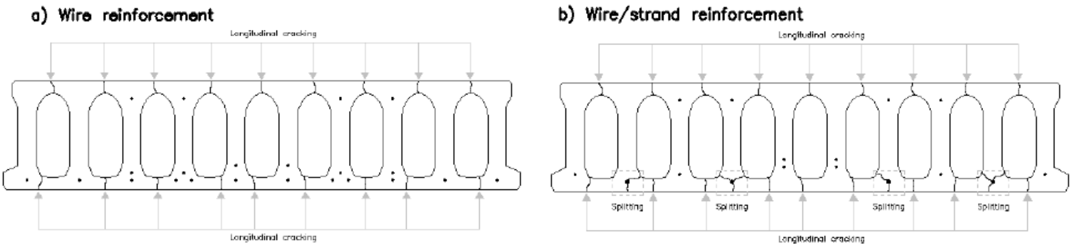


Figure 12: the cracking pattern [12]

From the previous investigations, it is obvious that there have been fewer studies concerning the isolation of HCS [2, 10]. The isolation location was away from the effect of temperature, either on the upper roof of the slab or in the voids. No attention is given to isolate the exposed surface of the slab. As a result, the isolation performed has no effect on the fire resistance of the investigated slabs. The author recommends isolating the exposed surface of slabs from fire directly or using concrete with good thermal properties [52].

Regarding the concrete cover and the strand arrangement, the latter is used to increase the thickness of the concrete cover, which is considered the main protection for strands. Although it is a reasonable solution for guarding strands, it reduces the design depth of the slab. Despite the fact that strands can be structurally positioned in the bending moment shape, this means they are protected from fire near supports for a simple beam. Unfortunately, the maximum stress is in the middle part. Undoubtedly, increasing the cover thickness to enhance FR is preferred, but with a limit.

2.4. Failure mechanisms

Numerous investigations were carried out on prestressed concrete HCS at high temperatures, these researches concern the crucial temperature and failure mechanisms of both concrete and prestressing steel. The production of HCS does not permit adding crosswise reinforcement. Hence, shear stresses and f_t from the transmission of the prestressing force must be supported by concrete itself. The same for positive bending stresses due to the prestressing moment. Figure 13 shows possible failure mechanisms and relevant serviceability limit states for prestressed HCS. [23]

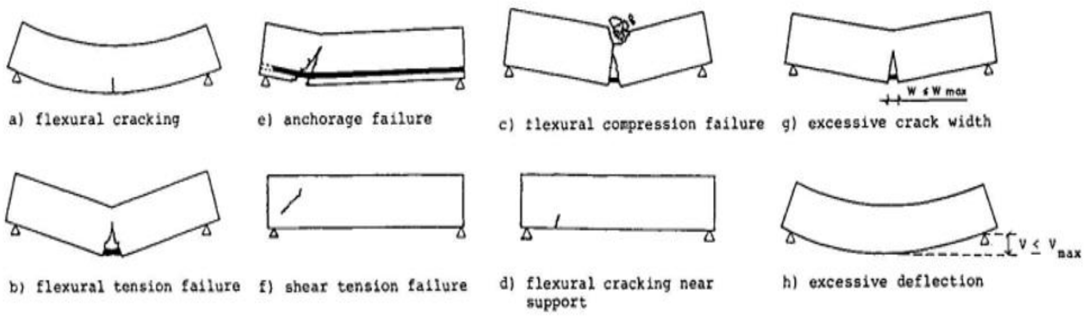
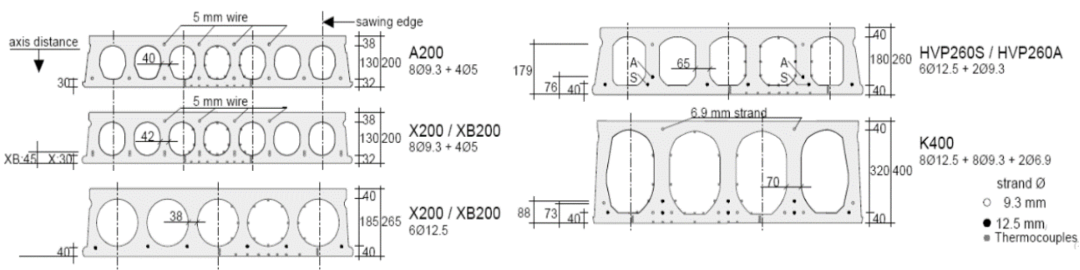


Figure 13: Possible failure mechanisms for HCS [23]

During fire tests, more than one type of failure mode may occur, or one after another may be observed. The behavior of HCS until failure and the type of failure is significantly controlled by longitudinal restriction [8, 11, 53], Support details [8], slab thickness [8, 19, 53], loading pattern [19] or level [9, 53]. HCS can fail through a shear limit condition before failing flexural in some conditions [19].

Fellinger (2004) concluded after his experiment on HCS that first, longitudinal restriction for thermal expansion may significantly enhance shear and anchorage failure, Support details were considered to note the anticipated cracks along the webs and assess the slip beneath the concrete and strands. Strand temperature is not a useful indicator because the greater the axis distance of the strands, the greater the negative impact on shear and anchoring behavior. Thirdly, shear and anchoring failures are low and significant with slimmer slabs [8]. Figure 14 clarifies the vertical cracks that occurred over the whole length of the specimen due to incompatible thermal elongations. [8]



CS of HSC

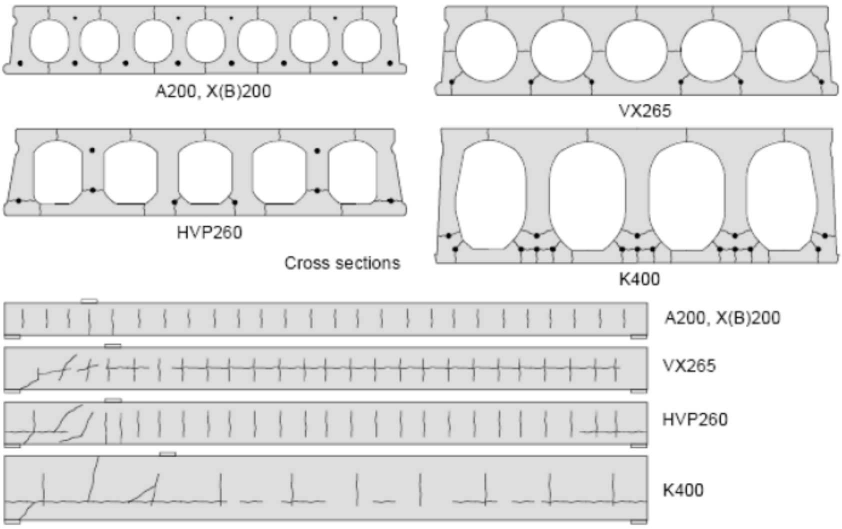


Figure 14 crack patterns for HSC [8]

Jensen (2005) provides a valuable insight into the slab's structural performance in terms of mid-span deflection with varied loading levels in terms of FR. HCS was composed of one whole and two half-length pieces that were 2935 mm long and 265 mm thick. Each piece has eight regular ribs in addition two longitudinal joints with side ribs. no spalling or breaking occurred in slabs with 65% and 75% loading based on shear capacity after 60 minutes of fire and 90 minutes of cooling. The slab with 80% loading in terms of ultimate shear capacity, failed after 45 minutes as a result of cracking. According the test findings, increasing the load has a substantial influence on FR. [9].

In reality, the majority of the evaluated studies fail to consider the relationship between the HCS slabs and the supporting element, which is significant and heavily influenced by actual fire. Damage to the vertical support was considered the primary mechanism of failure for HCS units at normal temperatures, and it resulted from the elongation of beams parallel to the hollow core span. The hollow core units were intended to function as simply supported beams [54].

Elevated temperature could cause rotation between the supporting beam and the slab unit due to the nonuniform distribution of thermal expansion revealed during a real fire. The loss of vertical support for hollow core units is caused by the sitting ledge collapsing or the hollow core unit being trapped at the seating, together with a starting bar rupture or concrete topping delamination. This depends on the length of the beams, the seating detail, and the elongation of the perimeter beams (cement grout or frictionless detail). This connection needs Numerous specific studies are required to protect this region when it is exposed to high temperatures.

From the above-reviewed research, the test parameters comprised the load level, concrete strength, cover thickness for reinforcement, and slab thickness. These fire tests, which included subjecting the slabs to typical fire conditions and service level loads, were primarily intended to acquire FR ratings for these slabs. The critical Temp. in a strand or the unexposed slab surface Temp. are often used as the limiting criteria to assess slab failure. The volume of fire-induced spalling and cracking phenomena in HCS was studied by a small number of researchers using data and observations from tests [1, 4, 7, 14–21].

Most previous fire tests were executed under conventional fire exposure with the sole goal of determining the ratings for HCS with defined configurations. Spalling, bond slide, and shear crushing were noted as potential contributory reasons for failure in HCS based on these fire tests [6–11, 21]. However, the effect of important elements on FR has not yet been properly defined, and the causes of the various HCS failure patterns have not yet been clearly identified. Furthermore, important factors like the fire scenario, the variety of loads, and the restraint circumstances were not taken into account in these fire tests. As a result, it is unclear how HCS would behave in actual fire, loading, and constraint scenarios. In order to get around some of these restrictions, finite element numerical (FE) models are being established for assessing the fire impact on HCS [19].

3. Numerical analysis models

Fire tests are expensive and time-consuming, so running multiple fire experiments to examine the influence of various factors on the fire performance of HCS is not possible. As a consequence, numerical simulations could be a suitable alternative to fire experiments. Furthermore, there aren't any restrictions on the characteristics that may be found in numerical modelling in order to analyse the behaviour of HCS more thoroughly.

There have been few numerical investigations into the FR of HCS, with the majority of these studies employing finite element-based models such as SAFIR [25, 27], DIANA 2000 [8, 26], FIRES T3 [10], COMSOL [28], ANSYS [19], or the new 2-phase computational model [29]. For the purpose of verifying the experimental tests, the ISO 834 standard was used. The majority of these studies had limitations because they did not consider important factors influencing the restraint of HCS during fire, such as the fire scenario, loading patterns, restraint conditions, aggregate type, and various failure mechanisms. Table 1 summarised the preceding numerical studies about the behaviour of HCS under fire and the crucial output of the study.

.Table 1. The previous numerical investigations concern the behavior of HCS under fire

Author/ Ref.	Model	The purpose of the study	The crucial Output of the study
Dotreppe and Franssen (2004) [25]	2D SAFIR	Evaluating the Impact of void distribution and the HCS constraint on deflection and cracking	Thermal stresses were highest during the initial 30 minutes fire. The cavities in the slab had a considerable effect on fire resistance Drawbacks; Spalling, Concrete strength and aggregate type were not examined.
Fellinger et al.	DIANA 8.1	The influence of the parameters on splitting	The FR is substantially impacted by the aggregate type, which affects the fracture energy and thermal

(2005) [8]		cracking, vertical cracking, and slide development The effect of aggregate type, constraint	expansion of the concrete. FR is largely impacted by the constraint to thermal expansion of the slab by lateral members. Drawbacks; Spalling was not examined.
Breccolotti et al. (2006) [10]	2D FIRES T3	Evaluating the effect of using LWC in HSC. Evaluating the load bearing capacity	Load bearing capacity, based on the bending failure criteria, was determined by thermo-structural analysis.
Engstrom et al. (2007) [26]	DIANA 8.1	Evaluating the influence of the parameters on the shear and torsion performance of the HCS	The models were effective in expecting the general behaviour, failure mechanisms, and extreme capacity that were in excellent accord with the experimental data Drawbacks; The model performs well at normal TEMP. but fails miserably at higher TEMP.
Chang et al. (2008) [48]	Simple technique	Testing a model predicting HCS FR. Evaluating the effect of varied configurations of axial and rotational restrictions at supports	varied configurations of axial and rotational restrictions at supports had a substantial impact on the fire behaviour of HCS. Drawbacks; shear, anchoring, and bond failures cannot be expected by the suggested model, resulting in no spalling occurring
Min et al. [27]	SAFIR	Evaluating the implications of starter (connection) rebars beneath the reinforcement topping slab and supporting beams.	Starting bars improves f_t at supports and, as a result, the FR of HCS. Drawbacks; Shear and bond failures could not be anticipated by the suggested model; The model implies no spalling happens.
Venanzi et al. (2014) [28]	COMSOL	The effect of spreading heat through the concrete and cavities through conduction, convection, and radiation. Evaluating the load bearing capability concerning the mechanical characteristics degradation of materials of HSC under fire.	Studying the thermal and mechanical issues individually did not result in significant problems since the expansion of HCS was permitted throughout the testing and the internal forces were independent of the thermal strain.
A.M. Shakya and V.K.R. Kodur	ANSYS	Evaluating the effect of Support conditions, geometric and material nonlinearities, reinforcing	The suggested model is able of describing the behaviour of HCS under standard and design fire settings since the time to failure is

(2015) [19]		and prestressing steel, as well as support conditions.	assumed to represent the slab's fire resistance
R. Peenko et al. (2019) [29]	Two-phase computational model	Figuring out the reaction of HCS subjected to fire, involving the heating and cooling stages using two-dimensional coupled hygro-thermo-chemical model	The output of the model validation demonstrated the suitability of the novel model for the investigation of prestressed HCS subjected to natural fire [29].
Albero V, Saura H (2018) [30]	A new Approach computational model	Identifying the extreme inexpensive slab design while considering all accessible production processes	When compared to standard circular void designs on the market, the best designs achieved by this approach save up to 20% in CS area When the fire-resistant restriction is addressed, typical designs are weak; the ideal design saved around 20% in CS. Drawbacks, Concrete strength and aggregate type, were not researched
Arajo and G. D. C. Pinto [31]	DIANA® 9.6	Predicting the presence of voids in the transversal CS of the slab	The 500 °C isotherm approach, however, showed that the standard FR of shallow HCS that are 16 cm high is less than values derived other tabular methods
Inwook Heo et al. in 2021 [32]	ABAQUS / CAE	HCS depth, span length, hollow ratio in a section, cover thickness of concrete and load ratio. The behaviour of HCS in terms of FR depending on each significant parameter was extensively analysed	The HCS's deflection considerably increased as the span length increased. But when HCS' vertical deflection was measured and verified with the limit deflection permitted by ISO 834-1, the normalized deflections showed equal values independent of HCS depth and span length. The calculation of the limit deflection approach presented in ISO 834-1 properly accounts for section depth and span effect.

4. Building standards limitations

4.1. Standard fire test

The exact criteria for measuring the FR of HCS are mainly based on the results and observations from routine FR testing. The test concluded exposing a structural element to a heating furnace for the requisite duration. FR rating data are presented as the duration that the member is able to tolerate the standard fire before a predetermined failure state is attained. Based on these findings, structural elements are designated as FR categories, for example, R30, R60, R90, R180, R210, and R240. The standard test procedures for determining the FR of precast prestressed concrete slabs are either the International Standard ISO 834 (ISO, 1975) [33], BS 476 (BSI, 1987) [34], or ASTM E119 (ASTM, 2011) [35]. Output of normal fire investigations are supplied by several testing codes, for particular, Underwriters Laboratories (UL) and Underwriters Laboratories of Canada (ULC) (ULC).

4.2. Codes and standards

Numerous governments all over the world demand buildings to comply with basic fire safety requirements. Usually, design standards comprise a variety of design procedures, which including tabular data, simple calculations, and complex processes. The data hierarchy differs in terms of implementation, with tabular data being the easiest and the most advanced procedures the hardest. Therefore, most design requirements are generally given by either tabular data or reduced calculations. The most well-known codes will be described in this section.

ACI 318

Structures made of precast and prestressed concrete are built in accordance with the American Concrete Institute's (ACI 318) standards and the Precast and Prestressed Concrete Institute Handbook (PCI 2010) [36, 37]. As a result, the PCI Handbook in the United States specifies the FR ratings for prestressed concrete.

Floor or roof slabs are illustrated in a tabular format depends on the concrete cover thickness for reinforcement. A logical design technique for assessing the FR of PC slabs based on the strength reduction of strands with Temp. is also put out in the PCI fire design handbook (PCI 2011) [38]. The provisions are purely normative in nature. The FR values do not take into consideration the elements impacting the FR and are based on the concrete cover of the PC slabs. It is predicated that less significant elements that affect heat transfer are concrete density, moisture content, air content, and maximum aggregate size.

ACI 216.1

Even though ACI 318 (ACI 318 2011) [37] lacks any fire requirements, it references the ACI 216.1 [39] standard, which provides prescriptive-based tables for FR ratings of concrete and masonry buildings based on ASTM E119 (ASTM 2011) standard fire tests [40]. In order to achieve the appropriate FR rating in slabs, ACI 216.1 [39] defines the minimum CS and concrete cover thickness over strands. The effective slab thickness for HCS is calculated by dividing the net cross-sectional area by the width. Additionally, the fire ratings for various end situations and aggregate types in concrete are included in both the PCI 2010 [36] and ACI 216.1 [39]. The rules in PCI 2010 and the International Building Code (IBC 2006) are comparable to those in ACI 216.1 [39] for assessing the FR of PC slabs (ICC 2012) [49]. The National Building Code of Canada is exclusively prescriptive in nature. The FR ratings depends on the concrete cover and the slab thickness and do not account for the factors influencing the FR.

Eurocode 2

Three methods are provided by Eurocode 2 [41] to assess the FR of PC slabs. These techniques, which include the tabular approach, the simplified approach, and advanced ways, are based on complexity. The first is the simplest and largest straightforward technique for assessing structural fire ratings; it is often identified as the prescriptive approach. The table represents FR depending on the slab's minimum thickness (excluding floor finishes), the reinforcement's axis distance (equal to the thickness of the concrete cover), and the various slab shapes (simply-supported, continuous, flat, and ribbed).

In Eurocode 2 [41], the streamlined method is based on CS analysis. Sectional analysis is used to assess the flexural capacity of the slab at any specified period of fire exposure while taking temp. -induced strength decrease variables into consideration. When the applied bending force exceeds the flexural capacity, failure in the slabs is presumed to have occurred; at this point, FR is assumed. Additionally, Eurocode 2-Annex G contains formulae for determining the shear and anchoring capacity of HSC in the presence of fire [41]. When the slab is exposed to a consistent Temp. and stress from fire, this approach may be used. The third way of assessing FR involves an advanced calculating method in which the thermal and structural response of concrete constructions is assessed using the concepts of heat transport and structural mechanics. Numerical computations must be verified using test data when using this strategy. There aren't any numerical models available for analyzing how prestressed concrete buildings respond to fire, despite the possibility that this technique might result in an accurate assessment of fire resistance.

The NBR 15200:2012

The NBR 15200:2012 [47] standard only offers a tabular approach to the fire design of concrete buildings; it includes no discussion of the design of hollow core slabs in its tables. Some criteria for the design of hollow core slabs in fire conditions are presented in the most recent revision of the Brazilian standard for the design of precast concrete structures, NBR 9062:2017 [48], but these criteria are only based on the minimum values for the hollow core slab's height and the distance from the strand reinforcement to the face of the structural element vulnerable to fire.

Others

Other design codes, such as the Australian Code AS 3600 (AS 3600 2001) [43], New Zealand Concrete Standard NZS 3101 (AS/NZS 2002) [44], and Canadian National Building Code (NRC/CNRC 2010) [45], contain FR rating tables in addition to PCI (PCI 2010) [36] and ACI 216.1 (ACI 216.1-14 2014). According to an assessment of current design guidelines in codes and standards, prescriptive-based techniques are the most common means of determining the FR of PC HSC, and these methods are mostly dependent on the critical strand Temp. of concrete. FR ratings are derived as a function of the concrete cover thickness for the strands and the slab thickness. The prescriptive procedures are developed only using the critical temp. in the strand as the limiting failure criteria, with no consideration for other critical failure modes.

5. Conclusions:

The main conclusions concerning the behaviour of HCS under fire, based on the previous investigation, are:

- The performance of HCS is influenced by a variety of variables, such as support condition, concrete aggregate type, slab thickness, fire insulation, cover thickness to reinforcement, spalling accessibility, void core arrangement and size, and firing methodology.
- Light weight aggregate and high strength concrete are typically recommended in HCS.As a result, it suffers severely from spalling when subjected to fire.
- Despite the fact that spalling is a major problem, the degree of fire-induced spalling and cracking phenomena in HCS has only been investigated by a few researchers. There aren't enough parametric studies on spalling; only test results and observations are recorded.
- Essential elements, including the fire situation, the range of loads, and the restraint circumstances, were not taken into account in these fire tests. As a result, it is unclear how PC hollowcore slabs will perform in actual fire, loading, and constraint circumstances.
- Most of the numerical studies had a lot of shortcomings; they omitted to take into consideration critical elements such as the fire scenario, loading patterns, restraint circumstances, aggregate type, and numerous failure mechanisms, which have a substantial influence on HCS performance in the presence of fire.
- Most states throughout the world mandate that buildings comply with basic fire safety rules. Typically, design provisions offer a hierarchy of design techniques, such as tabular data, simpler calculations, and advanced processes. The data hierarchy varies in complexity of application, with tabular data being the easiest and the most advanced approaches being the most demanding. Therefore, most design provisions are frequently produced by either tabular data or simpler calculations.

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