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VERIFICATION OF CODE FIRE RATINGS OF PRECAST PRESTRESSED CONCRETE SLABS

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Abstract. *In fire design for floors, the three criteria of stability, integrity and insulation are required for the specified fire resistance duration. Among these, stability is not easy to confirm. For solid prestressed concrete slabs of uniform thickness, Eurocode 2 provides tabulated data and specifies an axis distance to the centroid of strands to achieve particular fire resistance ratings, but it is not clear if this data can be used for a wide range of different prestressed slab profiles. In order to verify the current code-fire ratings for precast prestressed slabs, both simple and advanced calculation methods are investigated. This paper examines use of calculation methods, accounting for the real behaviour of unprotected simply supported prestressed concrete slabs exposed to the standard ISO 834 fire. The calculated fire resistance of each prestressed concrete slab is compared with tabulated data in Eurocode part 1.2, with detailed discussion.*

1 INTRODUCTION

Precast prestressed concrete slabs in multi-storey buildings have been widely used over the last decades in New Zealand and overseas. The floors have the advantage of off-site manufacture, long spans and high load capacity. Among the prestressed floors, the popular types are hollowcore slabs, tee slabs and prestressed flat slabs.

In their fire design, the three criteria of stability, integrity and insulation need to be satisfied for the specified fire resistance period. Integrity and insulation are usually dictated by the thickness of the slab and construction detailing to reduce gaps. Stability on the other hand is difficult to predict. As a result, standard fire testing is used to determine the stability of structures. However, this test is expensive and time-consuming, it is not ideal to test every floor configuration. As such, tabulated data of minimum thickness and axis distance exist in Eurocode 2 [1] and manufacturer data to achieve particular fire resistance ratings. However, this data is not always confirmed by fire tests [2] and has not been verified for a wide range of different prestressed slab profiles.

In order to overcome the limitations of current code-fire ratings for precast prestressed slabs, Eurocode 2 allows fire resistance to be assessed by a recognised calculation method. However, the simplified calculation methods included in Eurocode 2 are only appropriate for reinforced concrete structures. A special purpose, non-linear finite element program, SAFIR, developed at the University of Liege (Belgium), capable of conducting both thermal and structural analysis of structures, can be used to verify the implementation of the advanced calculation approach. The program can capture fundamental physical behaviour in thermal and mechanical behaviour in structural analysis of fire-exposed prestressed slabs.

This paper compares existing approaches of assessing fire resistance of prestressed concrete slabs in New Zealand, United States and Europe. The precast prestressed slabs considered are hollowcore slabs, tee slabs and prestressed flat slabs. They are all simply-supported but with different axis distances, and exposed to the standard ISO 834 fire. The thermal and mechanical properties of concrete and steel at elevated temperatures, used in the analyses, follow Eurocode 2 part 1.2. To simplify the comparisons, it has been assumed that spalling does not occur. In addition, advanced methods using finite element analysis are validated against the results of published fire tests [3] on prestressed concrete slabs. The time–temperature relationships, time–vertical displacement relationships and fire resistances of the prestressed slabs are evaluated by the finite element model. For each slab type, a relevant finite element model has been applied to evaluate fire resistance. The fire resistance of the prestressed concrete slabs obtained from the finite element analyses is compared with the design values obtained from Eurocode 2 at elevated temperatures.

The objective of this study is to examine the efficiency of using the various calculation methods (tabulated data, simple calculations and advanced calculations) to account for the real behaviour of unprotected simply-supported prestressed concrete slabs exposed to the standard ISO 834 fire. Key considerations that influence the fire resistance and behaviour of the prestressed concrete slabs are discussed for the different design approaches.

2 FIRE DESIGN OF PRECAST PRESTRESSED CONCRETE SLABS

Most countries throughout the world require structures to meet minimum fire safety requirements. Typically, design provisions offer a hierarchy of design methods, such as tabulated data, simplified calculations and advanced methods. The hierarchy varies in complexity of application, with tabulated data being the easiest and the advanced methods being the most complex. Therefore, most design provisions are typically established through either tabulated data or simplified calculations. However, in recent years performance-based methods have been introduced to give more flexibility to designers through the adoption of a rational approach. In this section, an overview of United States, European and New Zealand design provisions is presented.

2.1 United States

The American Concrete Institute (ACI) standards [4] references ACI 216.1 [5] for fire provisions of structural concrete members. The ACI provisions for prestressed concrete slabs are similar to the Precast/Prestressed Concrete Institute Design Handbook [6] and International Building Code [7]. These codes use tabulated data and simplified procedures to establish the fire performance of a prestressed concrete beam, as required by the ASTM E119 [8] standard fire test. Ratings are based on minimum concrete cover and depend on restraint and aggregate type. The tabulated prescriptive method gives fire ratings for 1, 1.5, 2, 3 and 4 hours for prestressed slabs. In addition, the PCI design standard, however, provides a simple calculation method for prestressed concrete slabs.

2.2 Eurocode 2

All reinforced and prestressed concrete structures are governed by EN 1992-1-1 [9], with their corresponding fire provisions given in EN 1992-1-2 [1]. The tabulated data, simplified calculations and advanced methods may be used. The quickest method to crudely determine the fire resistance of a prestressed slab is through the tabulated data. The tabulated prescriptive approach gives fire ratings for 0.5, 1, 1.5, 2, 3 and 4 hours. Ratings are based on minimum slab thickness and average axis distance of tendons to the exposed surface. The tables are also based on support conditions.

2.3 New Zealand

The New Zealand Concrete Standard NZS 3101 [10] uses tabulated data to establish the fire performance of prestressed concrete slabs. The ratings are based on minimum concrete cover. Through this parameter, the prescriptive method gives ratings for 0.5, 1, 1.5, 2, 3, or 4 hours.

3 FIRE DESIGN METHODS OF PRECAST PRESTRESSED CONCRETE SLABS

3.1 Tabulated data

Tabulated data is the easiest way to evaluate fire resistance of precast prestressed concrete slabs. A rating is given for each minimum axis distance. In order to meet the insulation criterion, the tabulated data also provides a minimum thickness, but an evaluation of the insulation criterion is not included in this paper.

3.2 Simplified calculation method

There is a general lack of simplified calculation methods for assessing the fire resistance of precast prestressed concrete slabs. For the current paper two calculation methods are considered: the step-by-step method and the PCI method. In both methods, failure occurs when the computed capacity is less than the applied moment.

3.2.1 Step-by-step method [11]

In the step-by-step method the surface temperatures, concrete temperatures and steel temperatures are determined for given fire temperatures using Wickström's formula [11]. In this method the flexural capacity of simply supported prestressed slabs under fire conditions is calculated by

$$M_f = A_s f_{y,T}(d - a_f/2) \tag{1}$$

where A_s is the area of the prestressing steel, $f_{y,T}$ is the yield stress of the prestressing steel at elevated temperature, d is the effective depth of the cross section and a_f is the depth of the rectangular stress block, reduced by fire, Thus, the fire resistance can be determined based on the tensile stress capacity of the prestressing strands as they lose their strength with increasing temperature.

3.2.2 PCI method [12]

The PCI method provides graphs showing the relationships between moment intensity and axis distance for various fire endurances in order to calculate the fire resistance. In principle, the theoretical moment capacity of prestressed concrete slabs can be calculated from the relationship

$$M_n = A_{ps} f_{ps}(d - 0.5a) \tag{2}$$

where A_{ps} is the area of the prestressing steel, f_{ps} is the stress in prestressing steel in flexural member at ultimate load, d is the effective depth of the prestressing steel and a is the depth of the rectangular stress block. Instead of an analysis based on strain compatibility, the value of f_{ps} can be taken to be

$$f_{ps} = f_{pu}\left(1 - 0.5\frac{A_{ps} f_{pu}}{bdf_c^{'}}\right) \tag{3}$$

where f_{pu} is the ultimate strength of prestressing steel, b is the width of the slab, and $f_c^{'}$ is the compressive strength of the concrete. From the calculations above, the moment intensity (M/M_n) and $\omega_p\ (=A_{ps}\ f_{pu}/b\ d\ f_c^{'})$ are determined. The fire resistance can then be obtained from charts, based on the aggregate type (e.g. see Figure 1 for siliceous aggregates). In the application of the PCI method, there are some limitations. As observed in Figure 1, the range of the moment intensity is limited to between 0.15 and 0.7.

3.3 Advanced calculation method

In order to critically evaluate the performance of advanced calculation methods, in comparison to simple calculations and tabulated data, the non-linear finite element analysis program, SAFIR [13, 14], was validated by comparing predictions from the model with measured data from fire tests on six prestressed flat slabs.

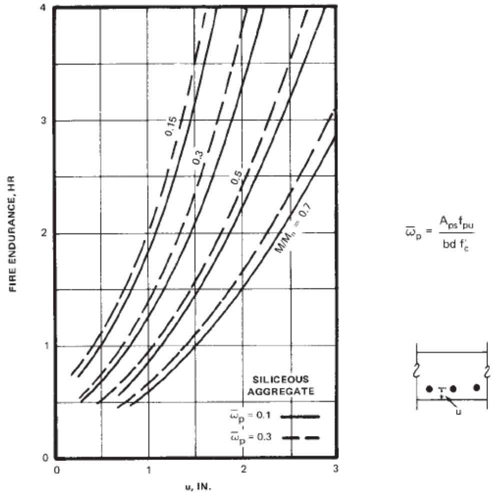
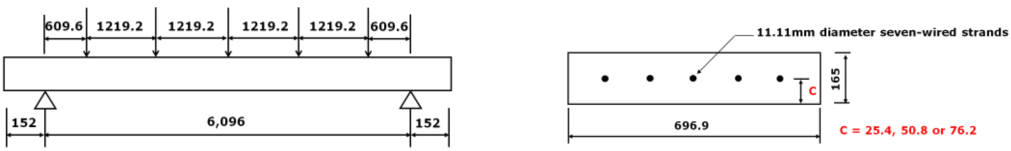


Figure 1. Fire endurance of prestressed concrete slabs as affected by moment intensity and axis distance [12]

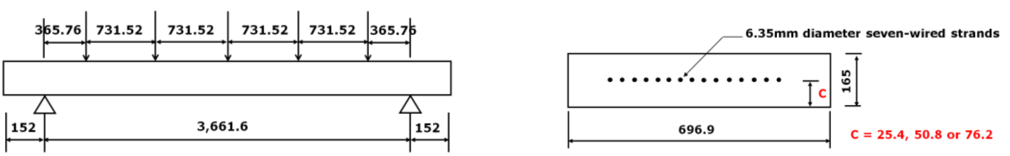
3.3.1 Fire tests

Fire tests on simply supported prestressed concrete slabs were performed by Gustaferro [3] in the United States. A total of eleven prestressed concrete slabs, were tested in accordance with ASTM E119 [15]. Six of the specimens were made of normal weight concrete, and the rest were made of lightweight concrete. As the aim of the paper is to compare results for normal weight concrete, the validation only considers the results for those tests with normal weight concrete. Figures 2(a) and 3(a) show the loading arrangements of the tested specimens. Of the six tests, three had specimens with five-11.1 mm diameter strands in a slab spanning 6096 mm, as shown in Figure 2(a). The other three specimens had fifteen-6.35 mm diameter strands in slabs spanning 3661.6 mm (see Figure 3(a)). All slabs were 696.6 mm wide and 165 mm thick in cross-section, as shown in Figures 2(b) and 3(b). Depending on the test, the strands had different cover thickness; 25.4 mm, 50.8 mm and 76.2 mm.



(a) Loading arrangement (b) Cross section of specimen

Figure 2. Specimen details for slabs with five-11.1 mm diameter tendons [3]



(a) Loading arrangement (b) Cross section of specimen

Figure 3. Specimen details for slabs with fifteen-6.35 mm diameter tendons [3]

Table 1 summarises the details of concrete strength and loading for each test. The measured ultimate tensile strength for the 11.1 mm diameter strand was 1806 MPa and 1896 MPa for 6.35 mm diameter strand. Partial loss of prestress was assumed to be 18%. The load intensity during the tests ranged between 40-60% of the calculated ultimate capacities.

Table 1. Specimen strength and loading details [3]

Slab Type	Concrete cover, mm	Concrete strength, MPa	Number and size of strands	Applied load, P (kN)
NWSLAB1	25.4	37.5	5-11.1 mm	5.77
NWSLAB2	50.8	34.7	5-11.1 mm	4.35
NWSLAB3	76.2	43.7	5-11.1 mm	2.86
NWSLAB7	25.4	35.7	15-6.35 mm	11.43
NWSLAB8	50.8	53.3	15-6.35 mm	9.05
NWSLAB9	76.2	37.4	15-6.35 mm	6.7

3.3.2 Finite element modelling of the prestressed concrete slabs

The finite element modelling of the prestressed concrete slabs begins with their thermal analysis. The cross-section of each prestressed concrete slab was modelled and analysed. It was assumed that the specimens were only exposed to fire on the bottom surface. For the structural analysis, the whole length of the specimens was modelled with 10 beam elements using the results of the thermal analysis.

3.3.3 Temperature distribution

Figure 4 shows the numerical results of the thermal analysis, highlighting the exposed and unexposed surfaces. It also shows the ASTM E119 and ISO 834 fires for comparison. A comparison of the thermal analysis and measured test temperatures is not presented, as temperature test data was not available. The exposed surface temperature increased to 1100°C during a 4-hour fire exposure. On the other hand, the temperature of the unexposed side in the numerical analysis was less than 300°C at the end of analysis. As a result, there is a large temperature gradient between the exposed and unexposed surfaces.

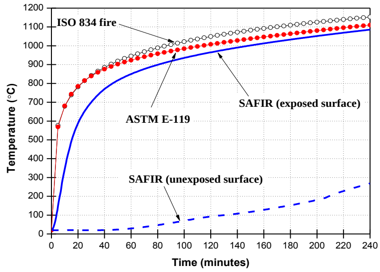


Figure 4. Comparison of temperature development between tests and numerical results

3.3.4 Comparison of numerical and test results

Figures 5, 6 and 7 illustrate the comparisons of central vertical deflections of the test and numerical results for specimens with five-11.11 mm strands. The comparisons with respect to specimens with fifteen-6.35 mm strands are shown in Figures 8, 9 and 10. All tests continued until the structural failure was imminent [3].

The SAFIR central deflection of the slab with five-11.11 mm strands and 25.4 mm cover thickness shows slightly lower deflections than their corresponding test results. On the other hand, the comparison of central vertical deflections of the equivalent slabs of five-11.11 mm strands with 50.8 mm and 76.2 mm cover thicknesses show better agreement between numerical and test data. In the earlier part of the fire exposure, the numerical result is observed to be stiffer than the test result. This is possibly due to shear deformation, which is not modelled in the numerical analysis. The commonly specified failure criterion (a deflection of span/20) is compared with the test and numerical results. It can be seen that for both cases (five-11.11 mm stands with 50.8 mm and 76.2 mm cover thickness) the numerical simulations accurately predict their behaviour for the duration of the fire. Both test and numerical results meet the failure criterion.

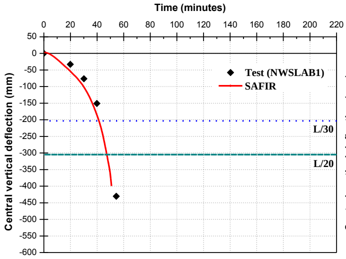


Figure 5. NWSLAB1

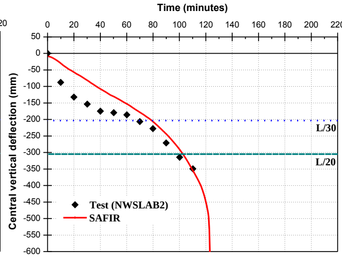


Figure 6. NWSLAB2

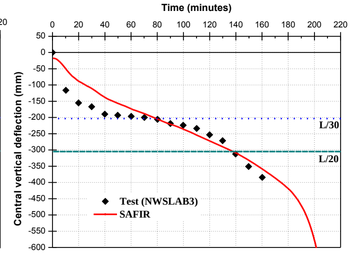


Figure 7. NWSLAB3

The comparison of central vertical deflections of test results and numerical simulations of slabs with fifteen-6.35 mm strands and 25.4 mm cover thickness shows that the numerical results are relatively stiffer than the corresponding test results, while those test results with 50.8 and 76.2 mm cover show a much better agreement throughout the fire exposure.

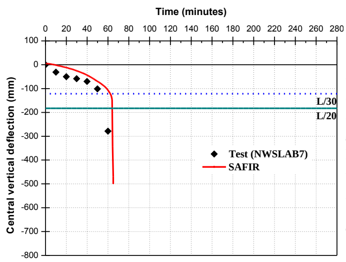


Figure 8. NWSLAB7

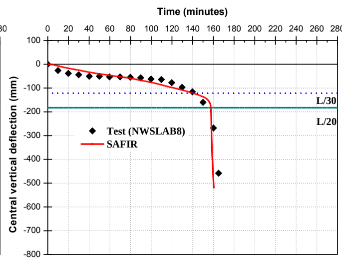


Figure 9. NWSLAB8

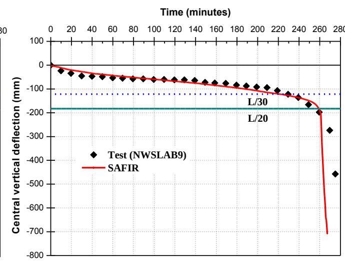


Figure 10. NWSLAB9

4 HOLLOWCORE SLABS

4.1 General

A 10 m long simply-supported 200 mm deep and hollowcore slab with 65 mm topping concrete was chosen to investigate the efficiency of each fire resistance design approach. The slab was 1200 mm wide. The strength of the precast concrete slab and topping concrete were 45 MPa and 30 MPa respectively. Seven 12.9 mm diameter, stress relieved seven-wire strands were used. The yield strength of the prestressing steel was 1.87 GPa. With a self weight (G) of 3.88 kPa and a live load (Q) of 3.3 kPa, the total load on the hollowcore slab in fire conditions was 5.53 kPa.

4.2 Results

Figure 11 shows time-vertical deflection relationship of the simply-supported hollowcore slab with axis distance varying from 25 – 55 mm. The cases with 70 and 80 mm axis distance could not be modelled because they could not be realistically manufactured.

Comparison among the tabulated data, the simplified calculation results and the advanced calculation results in terms of failure time is shown in Table 3. In the simplified calculation methods, the voids of a hollowcore slab are not considered as the fire resistance is only determined by the reduced moment capacity caused by the reduced tensile stress of the prestressing strands. It can be seen that the simplified calculation approach gives longer predictions of fire resistance, compared to the tabulated data. On the other hand, the advanced calculation method provides conservative prediction for low axis distance while the method is unconservative for axis distance of 55 mm or more.

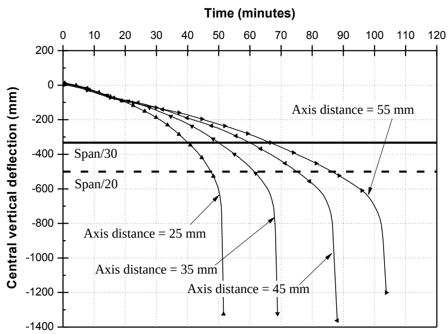


Figure 11. Comparison of central vertical deflection for 10 m span at each axis distance

Table 3. Comparisons of fire resistance for a single 200 mm deep hollowcore slab

Eurocode 2	Tabulated data (minutes)	Simple calculation methods (minutes)		Advanced calculation methods (minutes)		
Axis distance (mm)	Solid slab	Step-by-step method	PCI method	Span/30	Span/20	End of analysis
25	30	68	65	40	47	51
35	60	102	85	50	61	68
45	90	142	135	60	75	88
55	120	182	150	66	86	103
70	180	245	200	Not available (geometric problem)		
80	240	286	230	Not available (geometric problem)		

5 TEE SLABS

5.1 General

A simply-supported 500 mm deep, 150 mm wide, 14 m long, single-tee slab with 75 mm topping concrete was chosen to investigate the three design approaches. The slab was 1200 mm wide. The strength of precast concrete and topping concrete were 45 MPa and 20 MPa respectively. Five multiple strands were used along the height. The yield strength of prestressing steel was 1.86 GPa. The total load applied at the fire limit state was 6.25 kPa.

5.2 Results

Figure 12 shows a plot of vertical deflection with time for the simply-supported single tee slab with increasing axis distance. For tee slabs, multiple strands are used within their cross-section. As such the cases with 30, 60 and 90 mm axis distance were not modelled, due to the geometric limitations of prestressing strand arrangements. With regard to tapered single or double-tee slabs, to-date no simplified calculation method is available. Even though the PCI method provides the temperature at the centroid of the prestressing tendons at each fire exposure time, i.e. 0.5, 1, 1.5, 2, 3 and 4 hours, these can only be used to assess the fire resistance at those specific times. Comparison between the tabulated data and the advanced calculation method, in terms of failure time is shown in Table 4. It can be seen that the advanced calculation method gives a conservative prediction of the fire resistance, compared to the tabulated data, as the bottom prestressing has less concrete cover and is quickly exposed to fire.

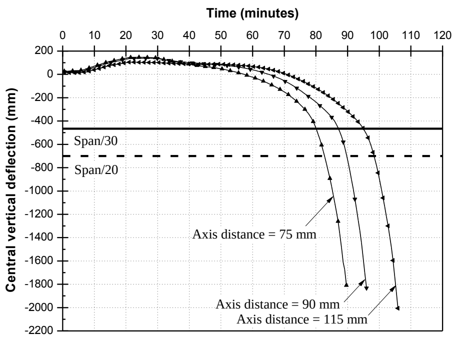


Figure 12. Comparison of central vertical deflection for 14 m span at increasing axis distance

Table 4. Comparisons of fire resistance for a 500 mm deep single tee slab

Eurocode 2	Tabulated data (minutes)	Advanced calculation methods (minutes)		
Axis distance (mm)	Ribbed slab	Span/30	Span/20	End of analysis
30	30	Not available (geometric problem)		
50	60	Not available (geometric problem)		
60	90	Not available (geometric problem)		
75	120	80	82	89
90	180	87	90	95
105	240	95	98	105

6 PRESTRESSED FLAT SLABS

6.1 General

A simply supported 75 mm deep and 6 m long prestressed flat slab with 130 mm topping concrete was chosen to investigate the fire resistance design, based on each calculation method. The slab was 1200 mm wide. The strength of precast concrete and topping concrete were 40 MPa and 20 MPa respectively. Eight 12.9 mm diameter, stress relieved seven-wire strands were used. The yield strength of prestressing steel was 1.84 GPa. A load of 9.65 kPa was applied at the fire limit state.

6.2 Results

Figure 13 shows the time-vertical deflection relationship of the simply-supported prestressed flat slab with increasing axis distance. Simplified calculations, using the PCI method were only carried out in the case with 25 mm and 30 mm axis distance as the other axis distances generated moments outside of the applicable range. Comparisons among the different approaches are shown in Table 5. It can be seen that in general, the tabulated data was the most conservative whilst the advanced calculation method produced longer times of fire resistance..

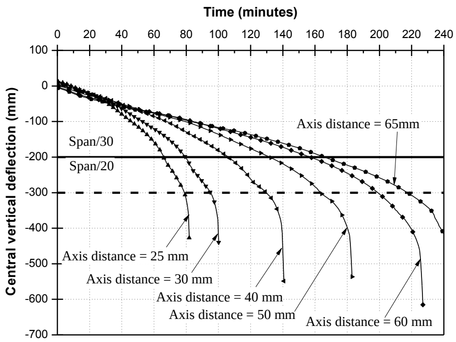


Figure 13. Comparison of central vertical deflection for 6 m span at each axis distance

Table 5. Comparisons of fire resistance for prestressed flat slabs

Eurocode 2	Tabulated data (minutes)	Simple calculation method (minutes)		Advanced calculation method (minutes)		
Axis distance (mm)	Flat slab	Step-by-step method	PCI method	Span/30	Span/20	End of analysis
25	30	56	45	65	78	81
30	60	70	50	79	95	100
40	90	96	Out of range (M/M_n =0.74)	106	129	140
50	120	118	Out of range (M/M_n =0.81)	132	163	182
60	180	140	Out of range (M/M_n =0.91)	157	199	226
65	240	148	Out of range (M/M_n =0.96)	165	217	Designated end time

7 CONCLUSIONS

The tabulated data for fire resistance of prestressed concrete slabs was compared with the results of, simplified calculation methods and advanced calculation methods. In all cases, the tabulated data is in general agreement with the trends from the calculation methods. For the advanced calculation methods, it is important to define the failure criterion, because large deflections can occur well before final failure. The use of a specified deflection, such as span/20, is recommended.

The results of the comparison are summarised below:

- For prestressed flat slabs, both the simple and advanced calculation methods give results larger than the EC2 tabulated data, generally with good agreement. The tabulated data appears to be on the safe side.
- For T-slabs, the advanced calculation method gives results much lower than the tabulated data, but only for a limited range of geometries.
- For hollowcore slabs, the simple calculation method gives higher fire resistance than the tabulated data. Whereas the advanced calculation method gives lower results because voids are included in the calculations, but not in the tabulated data. More research is needed for hollowcore slabs.

The numerical modelling approach used in the advanced calculation methods has been validated with some test results available in the literature, but the models do not accurately predict all possible failure modes. Due to the limitations of all calculation methods and lack of appropriate test results, more experimental and numerical research is needed to accurately predict the fire resistance of prestressed concrete floors in fire conditions.

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