Evidence of fire resistance of hollow-core slabs

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Abstract

Hollow-core slabs have during the past 50 years comprised a variety of different structures with different cross-sections and reinforcement. At present the extruded hollow-core slabs without cross-reinforcement in the bottom flange and usually round or oval longitudinal channels (holes) are predominant and in Denmark they are applied where fire resistances of 60- and 120 minutes are required.

In 2007 hollow-core deck elements with in-situ cast top concrete de-laminated during a fire in a car-park floor of a building in Rotterdam, where the bottom flanges of some decks fell down. A debate is therefore going on in the Netherlands about the fire resistance of hollow-core slabs.

In 2014 the producers of hollow-core slabs have published a report of a project called Holcofire containing a collection of 162 fire tests on hollow-core slabs giving for the first time an overview of the fire tests made.

The present paper analyses the evidence now available for assessment of the fire resistance of extruded hollow-core slabs.

The 162 fire tests from the Holcofire report are compared against the requirements for testing from the product standard for hollow-core slabs EN1168 and knowledge about the possible assessment of the fire resistance from the tests is derived.

For comparison a calculation approach is applied for the assessment in accordance to the product standard that refers to the Eurocode for concrete structures EN1992-1-2.

Key-words: hollow-core slabs, fire test, standard fire resistance, fire calculation

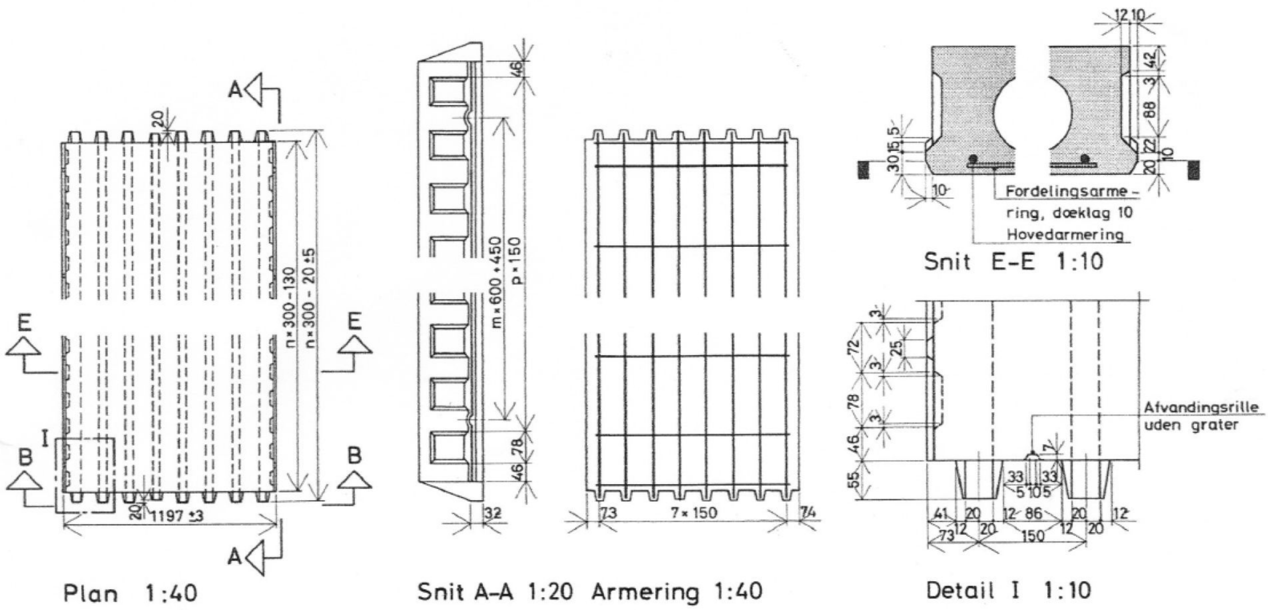

Figure 1. The classic hollow-core slabs with slack reinforcement and transverse reinforcement of the bottom flange [1].

Introduction

A hollow-core slab is a concrete slab with longitudinal holes or channels.
It was developed in the 1960'ies as a deck element suitable for industrialized buildings. The holes made it light and suitable for lifting it in place with a crane, but the hollow, light design also gave some negative effects in terms of poor sound insulation and a rigid rectangular lay-out of the buildings.

During time the production methods for hollow-core slabs have developed considerably. They are still slabs with holes, and therefore called hollow-core slabs, but the reinforcement lay-out, the reinforcement quality, and the concrete quality have changed, as well as the geometry of the grooves at the ends and at the sides of the elements.

The concept of hollow-core slabs covers now at least 4 designs with widely different fire resistance properties.

The original classic hollow-core slabs were 0.6 m or 1.2 m wide slabs with holes made by means of mandrels pressed into the concrete from both ends of the element.
These classic hollow-core slabs were dominant for the first 30-40 years.
The geometry and reinforcement of them are seen on Figure 1.
They had slack deformed bars as main reinforcement in the longitudinal direction and a mesh of mild steel was placed in the bottom. This means that the bottom flange under the holes was reinforced across the element, keeping the bottom flange in place.

Then a few factories started to produce 1.2 m wide hollow-core slabs with slip form casting. These had pretensioned reinforcement and were produced with transverse reinforcement in the bottom flange.

Finally, a new production method was applied and 1.2 m wide extruded hollow-core slabs with pretensioned reinforcement were introduced. The first of these decks appeared in Denmark around the year 2000. Extruded prestressed decks are the most widely used type of decks in Denmark today.

Lately, around the year 2010, a number of factories increased the width of the extruded decks to 2.4 m.

Due to the new production method, the extruded hollow-core slabs do not have transversal reinforcement in the bottom flange. As a consequence, the integrity of the bottom flange may be more easily endangered by fire.

However, since the new extruded pretensioned elements are still slabs with holes and are still called “hollow-core slabs”, few engineers, architects, or consumers recognize that the new versions applied today are different from the original classic hollow-core slabs.

The producers are usually responsible for providing the documentation for the properties of the elements and therefore other engineers involved in the building projects have no opportunity or interest in questioning it.

This confusion favours the idea that a 50 year long experience on hollow-core slabs is available as for example stated in [2]. However, the new extruded hollow-core slabs applied today cannot refer to this.

Figure 2. Damages after 25 minutes standard fire on two extruded hollow-core slabs with cast groove between and cast into a reinforced frame. Test from 2004 (H138 in [2]). Photo K. Hertz.

Previous investigations

In 1998 the Danish Institute of Fire Technology asked for a calculation of the fire resistance of a hollow-core slab prior to making a full scale testing. The calculation was made based on the presumption that the hollow-core slab was the original classic structure, and that the bottom flange would keep its integrity. The theoretical assessment based on calculation was about 60 minute's fire resistance, which is also known to be in good accordance with previous test results.

However, the slab elements were the new extruded version with no cross reinforcement, and the test result was about 25 minutes. The result caused a debate on the fire resistance of hollow-core slabs in Denmark. The debate resulted in a further test in 2004, where the fire resistance time was again found to be 25 minutes. As seen in Figure 2 the bottom flange of the slab fell down and large cracks were developed to the other channels.
Also in the mid 2000's a fire part of the Eurocode for concrete structures EN1992-1-2 [3] has been introduced based on previous work like [4, 5, 6]. Furthermore, a product code for hollow-core slabs [7, 8] was published, which referred to the chapters 4.2, 4.3, and to Annex B of the EN199-1-2 with respect to assessment of fire resistance.

The Holco-fire project

In 2007 a fire in a car park in a building in Rotterdam caused a number of hollow-core slabs to de-laminate and partially fall down [9].

In the Netherlands it is common to apply an in-situ cast top concrete to improve the performance of the hollow-core slab for example in order to fulfil the acoustic requirements.
Doing so, the top concrete and the top flange may act as a stiff massive slab without the thermal gradient that develops in the bottom flange of the hollow-core slab, when it is fire exposed. The bottom flange will therefore tend to deflect more than the stiff top slab, giving rise to tensile stresses in the webs between the holes. These stresses may cause splitting and de-lamination of the webs, so that the bottom half of the slab falls down.

In some cases the top slab seems to be so strong and stiff, and the load on the deck so little that the total slab does not collapse. However, it is obvious that the deck cannot have the load-bearing capacity intended.
The top flange of the hollow-core elements in Rotterdam was reinforced and so was the in-situ cast top concrete. The remaining top flange and top concrete therefore constituted a reinforced massive slab that in this case could carry the limited load on the deck so that only the bottom half fell down.

The Rotterdam fire caused a debate about the fire resistance of hollow-core slabs in the Netherlands, and a project was initiated by hollow-core slab producers to collect information on the subject.
In the spring of 2014, the International Prestressed Hollowcore Association (IPHA) published a report of a project called Holcofire [2].

The report lists 162 fire tests performed between 1966 and 2010, in order to account for the available documentation for the fire resistance of hollow-core slabs. Unfortunately, the report does not distinguish between the various production methods of hollow-core slabs. The associated test reports are not enclosed and usually not available, so it is not possible for the reader to know how the slabs are made, the test setup, or the loading. However, an overview of tests that are carried out is given in a table.

The table shows that a number of tests were made on slices of hollow-core slabs, on very narrow elements, and on systems of beams and decks. Furthermore, some tests were made on decks with fire insulation, with concrete topping, with reduced hole sizes, or with deck thicknesses or cover thicknesses greater than commonly used (Here this is defined as deck thicknesses > 350 mm or cover thicknesses > 50 mm).

Especially, a large number of tests were made on decks with short spans, so that the decks were not loaded in bending and thermal deflection and horizontal shear was limited. It therefore makes sense that the product standard for hollow-core slabs EN1168 [7] prescribes that the elements must have a length of at least 4 meters when testing.

Holco test #	Fire test name	Test year	Slab depth [mm]	Topping [mm]	Slab width [mm]	web	Strand mm2/slab	Axis dist mm	Length of test slab m	Width test set-up m	No. Of slabs	Test set-up	Time [min]
H96	DIFT X52650d	1998	185	0	1197	336	416	30	6.2	2.4	2	SYS	21
H97	DIFT X52650e	1998	220	0	1197	336	416	30	6.2	2.4	2	SYS	26
H98	DIFT X52650f	1998	270	0	1197	336	930	32	6.2	2.4	2	SYS	21
H137	IBS 07012911	2004	160	0	1200	259	468	48	5	3.6	3	SYS	94
H138	DIFT PG 11304	2004	265	0	1200	238	930	40	6.065	2.4	2	SYS	25
H139	ZAG 160/04-530	2004	320	0	1200	288	1209	35	5.12	2.4	2	SYS	105

Table 1. Relevant fire tests performed on hollow-core slabs during the last 20 years (1994 – 2014)

Test Results

If tests with decks shorter than 4 meters are deselected together with those tests that for the other above mentioned reasons are irrelevant, a systematic review of the tests shows that only 4 out of the 162 tests (H3, H50, H78, H79) have been tested for 120 minutes, but all these are more than 20-years-old and with unknown construction, load, and support conditions.

As explained, very different methods of production have been used over time to manufacture hollow-core slabs and the hollow-core slabs applied today are typically produced by extrusion, which does not allow for transverse reinforcement in the bottom flange of the deck's cross-section. It is therefore obvious that the documentation presented by the Holcofire project report for the hollow-core slab's fire resistance is partly based on production methods that are not applicable as a basis for documentation for fire resistance of the new extruded hollow-core slabs.

By analyzing the data presented, it is found that within the last 20 years there have only been 6 relevant fire tests of hollow-core slabs (H96, H97, H98, H137, H138, and H139), of which none demonstrated a fire resistance of 120 minutes.
Four of these tests were made at the Danish Institute of Fire Technology with fire resistance times of between 21 and 26 minutes (H96, H97, H98, H138).

As seen from Figure 2, 3, and 4 taken during test H138 the deflection of the slab was significant (actually the mid span deflection was 200 mm after 25 minutes) and the most likely failure mode of the slab was bending.

However, a debate has been going on from the assumption that shear should be the main problem for fire exposed hollow-core slabs, and several tests have been made on short elements in order to document the shear resistance.

But a short element cannot develop the same horizontal shear between web and the bottom flange beneath the longitudinal holes, and the mechanical and the thermal deflection are not the same as for a longer element. Therefore, a test of a short element cannot show the effect of loss of integrity of the bottom flange, and such test therefore cannot document how the shear resistance of the web between the holes is affected in a long hollow-core slab exposed to fire. It also cannot show whether the failure mode caused by the loss of integrity of the bottom flange will be shear, bending, or de-lamination.

Figure 3. Test H138 in [2]. Hollow-core slab after 25 min. Photo K. Hertz.

Calculations

The load-bearing capacity of hollow-core slabs during a fire is often in practice calculated under the prerequisite that the bottom flange of the deck remains intact. Detailed thermal calculations show that if the bottom flange is intact the temperatures at the bottom reinforcement can be assessed to be the same in a hollow-core slab as in a massive slab after 60 minutes fire exposure, but not later because then the isotherms are no longer horizontal (for example [10]).

However, tests and similar observations from actual fires (authors experience) show that the integrity of the bottom flange is a problem especially for the new extruded versions of the hollow-core slab without cross reinforcement in the bottom flange, because big cracks appear along the deck under the channels and often the bottom flange even falls down as for example shown in Figure 2 and 3.
Thus the prerequisites for the theoretically calculated temperatures are no longer present, and the increase in temperature in the webs and in the main reinforcement happens faster than assumed.

Figure 4. Test H138 in [2]. Cracks in top flange after approx. 15 min. Photo K. Hertz.

From the tests we see that the cracks in the bottom flange must be considered as serious after 10-15 minutes, where we also observe cracks in the top flange (Figure 4). The Holcofire report [2] states more precisely that the cracks in the bottom flange are formed after 6 minutes.

A more precise calculation method taking into account the simultaneous effects of bending, thermal gradients, thermal deformation, mechanical deflection, and horizontal shear on a bottom flange exchanging the shear between the web and the flange does not exist. If it emerges, it will require a considerable experimental documentation to evaluate it.

Regarding the short time before the integrity of the bottom flange is lost, a reasonable simplified calculation will be to omit the bottom flange at the holes and consider the ribs between the holes as exposed by fire from 3 sides from the beginning of the fire.

A formal calculation according to the product standard EN1168 [7] refers to 4.2, 4.3, and to Annex B in the Eurocode for concrete structures EN 1992-1-2 [3].
Annex B consists of two methods for calculating a reduced cross-section: method B1 was originally written by Yngve Anderberg and is based on removing material outside the 500C isotherm; method B2, which is considered slightly more accurate, was originally written by Kristian Hertz. The two methods give much the same result when used on hollow-core slabs.

According to Figure B5b in EN1992-1-2 [3], it can be directly seen that the damaged zone for a slab with a thickness of 150-250 mm, would be 36 mm after a 120 minutes standard fire and 20 mm for a 60 minutes standard fire. This means that the bottom flange of a hollow-core slab, which is usually about 34 mm thick, will be completely covered by the damaged zone after 120 minutes and the majority of it after 60 minutes.

This means that the reduced cross-section that should be considered according to EN 1992-1-2 [3] is not anymore a hollow-core section, but a ribbed cross-section, because the damaged unreinforced bottom flange cannot be taken into account under the holes, where there is nothing to support it.

The prestressing tendons in a new extruded hollow-core slab will often have a depth to the centre line of 34 mm. A finite difference temperature calculation (Confire [11]) of the temperature of a prestressing tendon with cover 34 mm to 3 sides gives 446C after 30 minutes of a standard fire, where the 0.2% yield strength of a cold-drawn prestressing wire is reduced to 24% of its original value and the load-bearing capacity in bending must be regarded as lost. If the temperature was assessed for smallest web thickness of 80 mm shown in the Eurocode [3] figure A3 you would get the temperature 420C for this slightly wider section confirming the result.

Furthermore, the prestressing tendons and their cover thickness will be comprised by the damaged zone, which is why the structural code cannot be used to document interaction between the reinforcement and the element (for example [12]).

The average compressive strength through the concrete web at 30 minutes in the example above is found to be 17% of the original, and shear or tension failure is likely to occur, which explains the splitting failure for example seen in the Rotterdam fire.

This seems to correspond well with the fire resistance time found from tests of the new extruded hollow core slabs, and it is seen that bending, shear, or splitting all are possible failure modes depending on the actual geometry and load.

Conclusion

New extruded hollow-core slabs are made without reinforcement in the bottom flange across the holes, and this is one reason why they cannot be compared with the classic hollow-core slabs for which we have about 50 years experience from practice.

From tests and real fires we can see that cracks are formed in the bottom flange of the new extruded hollow-core slabs and sometimes it falls down.

Calculations according to the product standard EN1168 with reference to EN 1992-1-2 clause 4.2 and 4.3 with Annex B show that the bottom flange does not preserve its integrity for the cross-section of the new extruded hollow-core slabs. It is therefore reduced to a ribbed cross-section.

Such calculations seem to accord well with findings from those tests in the Holcofire report that are made in accordance with the product standard EN1168.

Neither calculations nor tests are found to document a fire resistance of for example 120 minutes for the new extruded hollow-core slabs.

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