



Figure 6 - Column tested at DTU with 120x120 mm cross-section, 2% fibres, length 3898 mm, reinforcement 4Y16, maximum test load 1430 kN.



Figure 7 - Other columns tested at DTU. The one on the far right shows failure at a stirrup, while the centre column shows a cover to the reinforcement considerably larger than the nominal cover of 15 mm.

Figure 7 shows a few of the other columns tested at DTU. The picture indicates some of the other problems encountered in testing – and in interpretation of the results – as the column on the far right failed where a stirrup had been placed at mid-height of the column with a very small cover. Stirrups were used to keep the reinforcement in place, so they were either placed at a distance of 600 mm or in the case of the shorter columns stirrups were only used at the ends of the columns.

The column in the middle – with a cross-section of 120x120 mm and without steel fibres – definitely had a cover larger than 15 mm leading to a lower strength than expected. Spacers were used to maintain the cover, but investigations carried out after testing showed that while the minimum cover was adhered to with good precision, the cover could in some cases be up to 10 mm larger than expected. On the slender columns this kind of variation is very significant for predicting the ultimate capacity and will also cause eccentric loading and thus reduced capacity.

Based on the results shown in table 2, it is concluded that the formulas suggested here are applicable to a wide range of CRC columns. The formula was equally good at predicting results whether the columns had a low or a high slenderness ratio or whether they were round or rectangular. There was a slight indication that the safety factor in using the formula is reduced for columns with a large cross-section and a low slenderness index, as ratio1 in table 2 was very close to 1 for columns with cross-section 180x180 and 200x200 mm. Columns with no fibres were very brittle with a huge variation in test results. Based on the tests it was not possible to establish a difference in behaviour between fibre contents of 2, 4 and 6% - especially as only some of the columns were loaded to failure – but the general impression was that an increase in fibre content resulted in increased ductility. The formulas were originally developed in the Brite/EuRam project MINISTRUCT based on a very limited number of column tests.

For columns with eccentric load it is observed that test loads are always higher than predicted by calculation and the displacements at service capacity are smaller than expected – but very close to the calculated result.

3. COLUMNS LOADED UNDER FIRE CONDITIONS

3.1 Test programme

A number of projects have investigated the behaviour of CRC under fire conditions or at high temperatures. The most extensive project has been the HITECO project, which included testing of compressive and tensile strength as well as Young's modulus at high temperatures. These tests showed that while compressive and tensile strength was reduced at high temperatures, the loss in stiffness occurred earlier and was much more drastic – as is also observed for conventional concrete [8]. Earlier investigations have shown that even though CRC has a specific heat capacity and a thermal conductivity that differs from conventional concrete, the difference is sufficiently small that conventional approaches can be used also for CRC [9].

A total of 16 columns – all equipped with thermocouples - were tested in the current project at a fire load corresponding to the standard fire curve. The testing was done with hinges at the top and the bottom. The centre of rotation was placed so that the theoretical length of the columns was equal to the physical length plus 260 mm. The physical lengths are shown in table 7. The hinges allow for deflections in all directions. The load was kept constant during the test. Variations

included shape, dimensions, length, fibre content and size and amount of rebar. Also, one series of columns was tested with just a central reinforcing bar. 15 mm of cover to the rebar was used in general, except for the largest columns which had a 25 mm cover. In addition, to investigate heat transfer properties, 2 large slabs were exposed to a standard fire, one of CRC and the other of a high performance concrete similar to the type of concrete used in the Great Belt project in Denmark. This concrete has strength above 60 MPa and includes fly ash and micro silica. Thermocouples were placed at different depths in the 2 slabs as shown in figure 3. Thermocouples 1-3 were placed at a depth of 10 mm, 4-5 at 20 mm, 7-9 at 30 mm and thermocouples 10-12 were placed at a depth of 40 mm. The slabs were exposed from one side, while the columns were exposed to the fire from 4 sides.

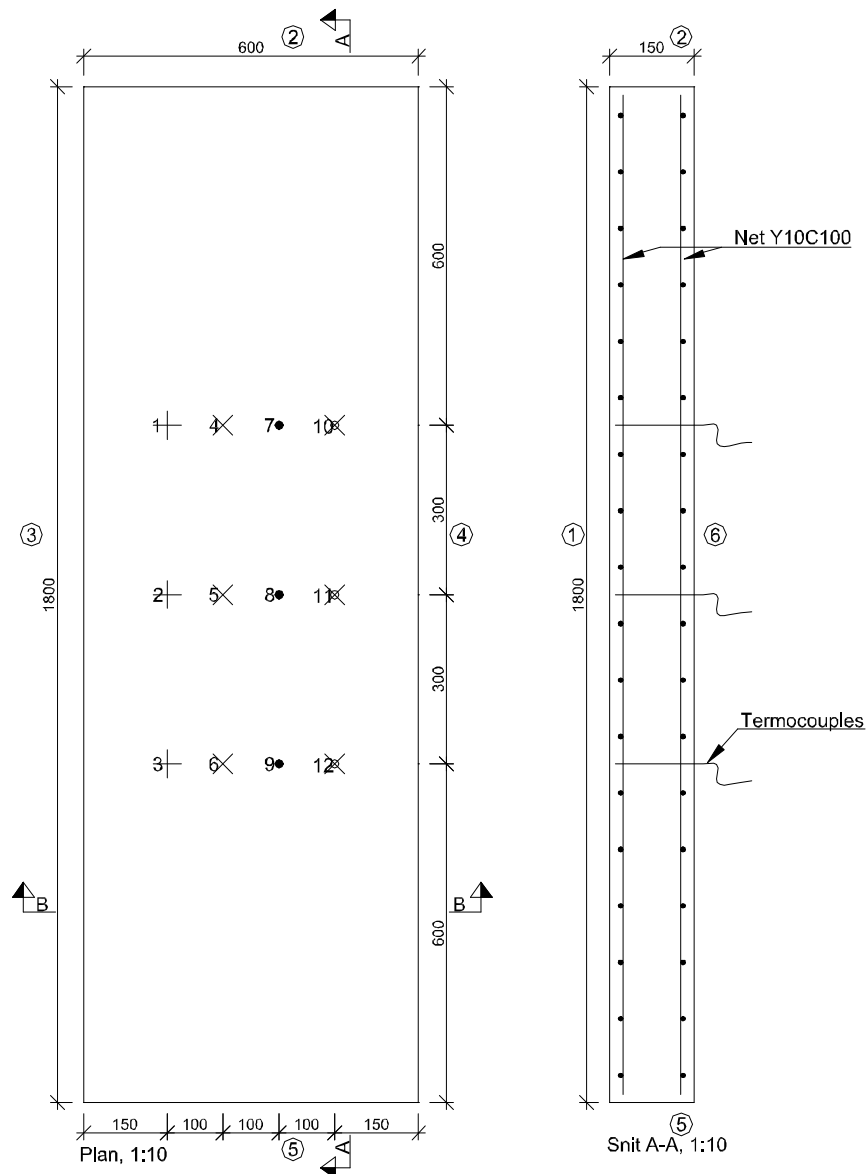


Figure 3 - Plan and cross-section of panel tested in fire exposure.

3.2 Results for slabs

Figure 4 shows a picture from the test shortly after it has started. Water is visible on the back of the slabs as it is driven out along the cords of the thermocouples. After 20 minutes it is clear that much more water is driven from the CRC slab and foam is also coming out. After an additional 15 minutes, hardly any water is coming from the conventional concrete, while there is still a lot of water coming from the CRC.

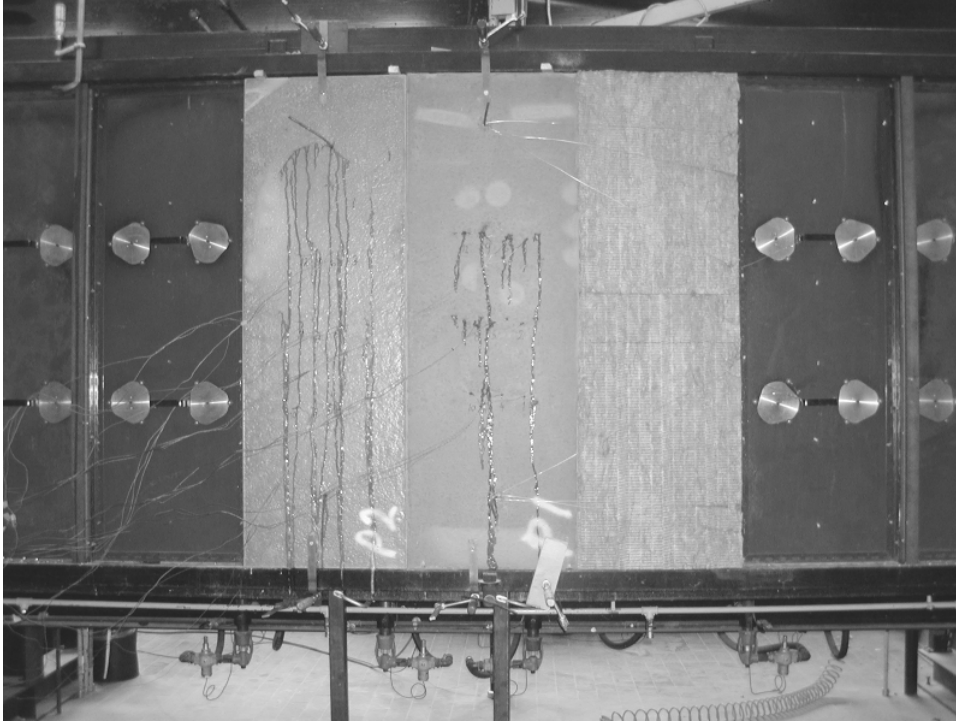


Figure 4 - Back of slabs during fire exposure. The CRC slab is the one on the left and insulation mats are shown on the right.

In tables 5 and 6 results are shown from measurements of temperatures in the 2 slabs after 30 minutes and 60 minutes. The mean value of the temperature is also shown for each depth. The measurements are compared with an estimated temperature and different ratios are shown in the table. The calculated temperature is found by using the basic calculation method from the Danish standard DS411 with the default properties for the concrete as shown below.

$$\theta_1(x,t) = 312 \cdot \log_{10}(8 \cdot t + 1) e^{-1,9k(t) \cdot x} \cdot \sin\left(\frac{\pi}{2} - k(t) \cdot x\right) \quad (7)$$

where:

$$k(t) = \sqrt{\frac{\pi \cdot \rho \cdot c_p}{750 \cdot \lambda \cdot t}} \quad (8)$$

x	:	distance from the surface in metres
t	:	time in minutes
λ	:	thermal conductivity in W/m°C – for normal concrete 0.75 W/m°C . The value is to be verified by tests.
ρ	:	density in kg/m ³ .
c_p	:	Specific heat capacity – for normal concrete 1000 J/kg °C

Table 5 – Measured temperatures – in °C – and mean values after 30 minutes of testing.

	10 mm cover		20 mm cover		30 mm cover		40 mm cover	
CRC	464		310		221		162	
	439	456	336	331	242	238	178	175
	464		346		252		185	
Concrete	291		256		187		159	
	336	320	280	271	205	196	141	152
	333		278		196		156	
DS411 value		491		310		186		104
CRC/concrete		1.42		1.22		1.22		1.15
CRC/DS411		0.93		1.07		1.28		1.68
Concr./DS411		0.65		0.88		1.05		1.46

Table 6 – Measured temperatures – in °C – and mean values after 60 minutes of testing.

	10 mm cover		20 mm cover		30 mm cover		40 mm cover	
CRC	670		512		401		304	
	636	652	535	530	411	415	331	323
	651		544		433		335	
Concrete	475		431		349		281	
	515	502	453	446	366	355	296	294
	515		453		350		306	
DS411 value		627		460		329		229
CRC/concrete		1.30		1.19		1.17		1.10
CRC/DS411		1.04		1.15		1.26		1.41
Concr./DS411		0.80		0.97		1.08		1.29

3.3 Results for columns

The results for the columns subjected to fire are shown in table 7.

*Table 7 - Results from the fire tests. * indicates that the column was not tested to failure.*

Cross-section mm	Length mm	Reinforcing bars	Fibre content %	Test load kN	Cover mm	Time min	Temp. at re. bar °C	Temp. at centre °C
120x120	3420	4 ø12	2	200	15	31	587 479	261
120x120	3420	4 ø12	2	200	15	27	551 412	201
120x120	3420	4 ø12	2	200	15	29	540 456	230
120x120	3420	1 ø25	2	180	15	22	158 130	
120x120	3420	1 ø25	2	180	15	32	241 234	
120x120	3420	1 ø25	2	100	15	36	221 308	
120x120	2725	4 ø20	2	160	15	58	690 672	505
120x120	2725	4 ø20	2	130	15	62	784 732	547
120x120	2725	4 ø20	2	160	15	55	748 690	533
Ø 150	3420	4 ø20	4	180	15	58	781 659	531
Ø 150	3420	4 ø20	4	180	15	52	655 630	563
Ø 150	3420	4 ø20	4	160	15	62	728 669	514
200x200	3420	4 ø20	2	400	25	79*	721 762	649
200x200	3420	4 ø20	2	1000	25	60*	551 436	201
200x200	3420	4 ø20	2	1000	25	89	700 615	318

The temperatures in the columns were typically measured with 10 thermocouples, but not all of the results have been included in the table. The two values given at the reinforcing bar are from thermocouples actually placed on the bars. The first value is an average from the thermocouples placed on two different bars as close to the surface as possible, while the second value is an average from the thermocouples placed on the same two bars, but at the “back” of the bar. In some cases the difference between two values that should ideally have been the same – and which are just given in the table as an average – was up to 100 °C. In the case of the column with one central reinforcing bar only two thermocouples are placed on the bar and they are spaced 90° apart. In the case of the central bar, there is no measurement from the centre of the column. The values measured on the reinforcing bars are generally higher than the values measured with other thermocouples, which are placed at an equivalent depth in the concrete.

The temperatures shown are measured at the end of the test and they will thus vary from one column to another as exposure time was different for each column. The table also shows the test load, which was kept constant for the duration of the test, and the test time. Typically the test was continued until the column had very large deformations. The columns did not actually break, but sustained a very ductile failure as can be seen in figure 9. In a few cases – indicated with * in table 7 - the test was stopped while the column was still able to carry the load with no problems.



Figure 9 - Some of the columns after fire exposure.

3.4 Discussion

In general the columns had a lower fire resistance than expected. As shown in table 7, most of the columns have a fire resistance time shorter than 1 hour. This was also the case for the columns that have a central reinforcing bar, which is a bit surprising as the temperature at the rebar is only a few hundred degrees. However, with the slender columns the heat capacity is limited and the increase of temperature overall is high. This has led to a decrease in stiffness, which – along with an effect of thermal stresses - from the appearance of the columns after testing has had more influence on the fire resistance time than reduced strength of the reinforcement. As mentioned earlier at high temperatures the reduction in Young's modulus will occur faster than reduction in strength for CRC – as for conventional concrete – which is a problem for slender columns.

In order to be able to test the columns at an early age, the columns had been dried out in a humidity chamber and in a number of cases this had led to some curvature even prior to testing. This was possibly due to reinforcement that was not properly placed or it could be caused by the columns only being supported at the ends during drying. This initial curvature and possible internal eccentricity from the placing of the reinforcing bars causes eccentric loading and reduces the fire resistance time observed in the tests.

Based on evaluation of the results – and of results from earlier tests in the HITECO project – it is difficult to establish design rules, but some general guidelines – in the form of a list of examples - can be established. As an example a column with $\varnothing 150$ mm cross section, 2% fibre content, 4Y20 bars with a minimum cover of 15 mm and a length of no more than 3420 mm is considered BS60 – capable of sustaining a standard fire for 60 minutes – provided the central load is below 160 kN.

4. CONCLUSIONS

A number of columns have been tested in the project, including tests with central load and eccentric load under ambient conditions and with central load under fire conditions. The columns were designed to cover a range of variations in parameters such as slenderness, shape, size, reinforcement, fibre content etc.

The tests carried out in ambient conditions – for central and eccentric load - showed good correlation between test results and expected bearing capacities calculated according to design guides established based on earlier CRC investigations. In general the CRC columns tested in ambient conditions can be shown to have a capacity equivalent to that of a corresponding steel tube column of similar cross-section and length.

The fire resistance tests demonstrated that the slender columns were very sensitive to thermal stresses and changes in stiffness due to high temperatures – as well as to imperfections prior to loading. Thus very slender columns failed early in the tests even though temperatures at the reinforcement were low. Failure was always ductile and there was no spalling. Not all columns were tested to failure and it was demonstrated that fire resistance above 1 hour can be achieved.

The results of the project have already been utilised in a number of projects where CRC columns have been used. Generally, slenderness is kept below 3.5 to avoid premature failure in case of fires.



Figure 10 CRC Balcony slabs and columns produced by Hi-Con at Askehaven, Vejle in Denmark.

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