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RAPPORT

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Paper presented at CIB-W18, Meeting 25, Åhus, August 1992

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INSTITUTET FÖR TRÄTEKNISK FORSKNING

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TESTS ON GLUED LAMINATED BEAMS IN BENDING EXPOSED TO NATURAL FIRES

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SUMMARY

A series of fire tests with so-called natural fire exposure of loaded glued laminated beams was performed. The fire exposure on three sides during the tests was governed by a temperature-time relationship determined according to an energy balance method (opening factor method) with different fire load densities and opening factors. The results confirmed the rate of charring on the wide side of the member obtained by Hadvig. The average charring depth on the lower side of the member was greater than the average charring depth on the wide side when the width of the lower side was smaller than about 180 mm. Considering the mechanical behaviour, the tests showed that a loss of strength and stiffness of the residual cross section occured, and that it continued through the cooling period, caused by continous heat flow to the inner parts of the cross section.

INTRODUCTION

In most structural fire design codes the fire load is given by the standard fire temperature-time curve according to ISO 834. For this type of fire exposure the behaviour of a wood member is fairly well-known for large cross sections: In practical design applications, charring is assumed to occur at an approximately constant rate and the influence of the fire exposure on strength is limited to a depth of about 40 mm below the char-line. For this type of cross sections a very simple model for design can be applied. According to this model a zero-strength layer with a thickness of about 7 mm is removed from the residual cross section, and the remaining part of the residual cross section, i.e. the effective cross section, is assumed to have full strength as in normal design.

So-called natural fires include both the period of increasing temperature and, after the combustible material in the fire compartment is consumed, the subsequent period of cooling. The rise of temperature and the length of these periods is dependent on the fire load and the number and size of openings. Such design method has been used in fire design in Denmark and Sweden for many years, and it is considered to be included in Parts 10 of Eurocodes - Structural Fire Design. Charring of timber under such fire conditions has been investigated by Hadvig /1/. The results of this research were adopted in the Danish Building Code for determination of the charring depth of members in timber structures. Since Hadvig did not perform fire tests with loaded specimens, and there did not exist any experience on the material properties of full-size glued laminated members under such conditions, a series of fire tests was performed at the University of Aalborg under the leadership of F Bolonius Olesen.

The time-temperature relationship in natural fires is dependent of the fire load q_t and the opening factor F of the fire compartment. The opening factor is defined as

$$F = \frac{A}{A_t}\sqrt{h} \qquad [m^{\frac{1}{2}}] \qquad (1)$$

where
- A total area of vertical openings (windows etc.) in m^2
- A_t total area of floors, walls and ceilings which enclose the fire compartment in m^2
- h weighted average of heights of all vertical openings (windows etc.) in m.

The charring rate of the wide side of a member in natural fires can, as a simplification of Hadvig's expressions, be described as a function of time according to Figure 1. The initial charring rate β_0 is constant during the time period t_0 with increasing gas temperature in the fire compartment, and the charring rate decreases then until the maximum charring depth is reached after the total time $3t_0$, even though the cooling period is not terminated. The parameters β_0 and t_0 are defined as

$$\beta_0 = \frac{5F - 0{,}04}{4F + 0{,}08} \qquad \left[\frac{mm}{min.}\right] \qquad (2)$$

and

$$t_0 = 0{,}006\,\frac{q_t}{F} \qquad [min.] \qquad (3)$$

where the fire load q_t is in MJ/m^2 and F is given by Equation (1).

The Equations (1) and (2) are valid for an opening factor F between 0,02 and 0,30 $m^{1/2}$, a time period t_0 of not more than 40 minutes and a maximum charring depth on the wide sides of one fourth of the width of the narrow side of the beam.

FIRE TESTS

The test series included 18 full-scale tests with static loading, and 30 additional tests with unloaded specimens for temperature measurements inside the beams. These tests are described in a preliminary test report /2/. A report with the complete test data is in preparation /3/. In this paper the results of nine of the full-scale tests and of one of the additional tests are reported.

The test specimens fullfilled the requirements of strength class L30. The flexural stiffness of each beam was determined prior to each fire test.

The tests specimens of glued laminated timber with a span of 3,60 m were acted upon by two point loads in symmetrical position, the distance between them being 0,9 meters. The middle part of the beam with a length of 2,8 m including the loading devices were inside the furnace. The test beams had the nominal initial depth h_0 of 300 mm and the nominal initial width b_0 of 140, 160 or 185 mm. They were exposed to fire on three sides, the upper side was protected by means of mineral wool batts.

The fire exposure during the tests was governed by a temperature-time relationship determined according to an energy balance method (opening factor method) with different opening factors F and fire load densities q_t. See Table 1.

The initial static loading P_0 in each loading point was 5, 7 and 8 kN respectively and held constant during the major part of the fire tests. The load level was chosen to be low in order to prevent lateral buckling, since the beams were not braced during the period of fire exposure. When the gas temperature in the furnace had decreased to about 300 to 250 °C the fire was extinguished with water, bracings were attached to the test beam, and immediately after the static loading was increased until the failure load P_u of the beam was reached.

The deflection of the beams was measured at two points at distances of 150 and 750 mm from the middle of the beam.

Temperature measurements in the test specimens were made using thermo-couples.

After the tests the char layer was removed by means of brushing off the char and the charring depth was measured at five gauge points located in the transverse direction of the beam. In the case of a long fire exposure duration it was practically possible to make measurements only at the middle three gauge points.

TEST RESULTS

Typical test results are presented in Figures 2 to 4, showing the time-dependent temperature in the furnace, and the corresponding deflection of the test beam at the two gauge points. The indices in the notations refer to the distance of the gauge point from the middle of the beam in centimetres. The figures represent the fire load conditions according to Table 2.

It is obvious that the deflection of the beams increases during the whole cooling period at about the same rate as in the initial period with increasing temperature. The rate of loss of stiffness is not affected by the fact that the maximum charring depth is already reached at the time of $3t_0$ according to Equation (3), which is considerably smaller than the time at which the load was increased.

In Figure 5 typical temperature-time curves are shown. The temperature in the outer parts reaches its maximum in the first part of the cooling period and is affected by the decreasing temperature in the furnace. The temperature of the gauge points in the inner of the cross section continues to increase during the whole test period and exceeds 100 °C even in the midle of the cross section.

The average charring depths are given in Table 3.

where $d_{char,w}$ average charring depth on the wide side
$d_{char,n}$ average charring depth on the narrow side.

The agreement of measured and calculated values on the wide side according to Hadvig /1/ is good.

Due to two-dimensional heat flow near arrisses, charring is greater on the narrow side than on the wide side, see Figure 6, where the ratio $d_{char,n}/d_{char,w}$ is shown versus the initial width b_0 of the narrow side. This effect becomes negligible when the width of the narrow side is greater than about 170 to 180 mm. According to Hadvig this effect can be disregarded when the width of the narrow side is at least 80 mm. This result is in contradiction to Hadvig's results. Since the number of tests is limited and the variation of measured values on the lower side was considerable, this result should be regarded as preliminary.

Using the depth h_r and width b_r of the residual cross section, i.e. the initial cross section minus the char layer, the bending strength $f_{m,r}$ was calculated. If we assume that the bending strength of the test beams at normal temperature was 40 MPa (the mean bending strength of Nordic glued laminated timber is about one third greater than the characteristic value), the bending strength ratio

$$k_r = \frac{f_{m,r}}{f_m} \tag{4}$$

of the residual cross section, see Table 3, can be presented as a function of the relative charring depth $d_{char,w}/b_0$, see Figure 7. The regression line is

$$k_r = 0{,}98 - 3{,}02 \frac{d_{char,w}}{b_0} \tag{5}$$

For comparison this has been done also for f_m = 30 MPa.

This relationship shows that the amount of charring, or indirectly the duration of time, is important for the reduction of bending strength of the residual cross section. With increasing charring a greater part of the cross section is affected by elevated temperature caused by continuous heat flow during the cooling period.

For comparison, for standard fire exposure, a typical value of the bending strength ratio is 0,8. Values of this order of magnitude are used in some national fire design codes.

With

$$d_{char,w} = 2\ \beta_0\ t_0 \tag{6}$$

see Figure 1, and substitution of Equations (2) and (3) we get approximately

$$k_r = 1{,}0 - \frac{q_t}{27\ b_0\ F}\ \frac{5\ F - 0{,}04}{4\ F + 0{,}08} \tag{7}$$

Thus the bending strength ratio for three-sided fire exposure can be expressed by the width of the narrow side, the fire load and the opening factor.

CONCLUSIONS

In structural fire design the charring rates obtained by Hadvig /1/ according to Equations (2) and (3) and Figure 1 should be used for the wide vertical sides of a member. The charring rates on the narrow side according to Hadvig could not be confirmed. The reason for this might be that the number of tests was too small.

Compared to the conditions at standard fire exposure, the mechanical behaviour at natural fire exposure is different due to the changes of temperature in the residual cross section during the cooling period. In natural fires the bending strength and stiffness is lower than in standard fire. The influence of elevated temperature is no longer concentrated to the outer layer of the residual cross section. Thus the concept of a reduced bending strength of the residual cross section should be applied, e.g. by using a bending strength ratio similar to Equation (5).

REFERENCES

/1/ Hadvig, S., Charring of wood in building fires. Technical University of Denmark, Lyngby, 1981.

/2/ Bolonius Olesen, F., Brandteknisk dimensionering af limtrækonstruktioner. University of Aalborg, 1992

/3/ Toft Hansen, F & Bolonius Olesen, F., Full-scale tests on loaded glulam beams exposed to natural fires. University of Aalborg, 1992

Table 1 Test data and results

No.	h_0	b_0	F	q_t	P_0	P_u
	mm	mm	$m^{1/2}$	MJ/m^2	kN	kN
G 07	298	137	0,04	126	5,0	12,6
G08	296	136	0,06	113	5,0	22,0
G 09	296	136	0,08	151	5,0	20,6
G 23	298	158	0,04	126	7,0	16,7
G 25	298	158	0,08	251	7,0	13,2
G 26	299	158	0,08	151	7,0	30,1
G 32	299	184	0,04	188	8,0	11,6
G 33	298	183	0,06	188	8,0	19,6
G 34	297	183	0,08	251	8,0	19,8

Table 2 Some typical fire load conditions

	Fire load	Opening factor	Time
G 07	small	small	medium
G 09	small	large	short
G 32	medium	small	large

Table3 Test results and evaluation

No.	$d_{char,w}$ test	$d_{char,n}$ test	$3t_0$ calc.	$d_{char,w}$ calc.	h_r	b_r	$f_{m,r}$	f_r / 40	f_r / 30
	mm	mm	min.	mm	mm	mm	MPa	-	-
G 07	24,1	32,2	57	25,2	266	89	16,2	0,405	0,540
G08	16,4	17,7	34	18,4	278	103	22,4	0,560	0,747
G 09	20,3	22,8	34	20,4	273	95	23,6	0,590	0,787
G 23	26,0	28,3	57	25,2	270	106	17,5	0,438	0,583
G 25	32,0	36,9	56	33,9	271	94	15,5	0,388	0,517
G 26	20,0	22,3	34	20,4	276	118	27,1	0,678	0,903
G 32	38,9	40,4	85	37,6	259	106	13,2	0,330	0,440
G 33	29,4	26,4	56	30,7	272	124	17,3	0,433	0,577
G 34	34,1	30,6	56	33,9	266	115	19,7	0,493	0,657

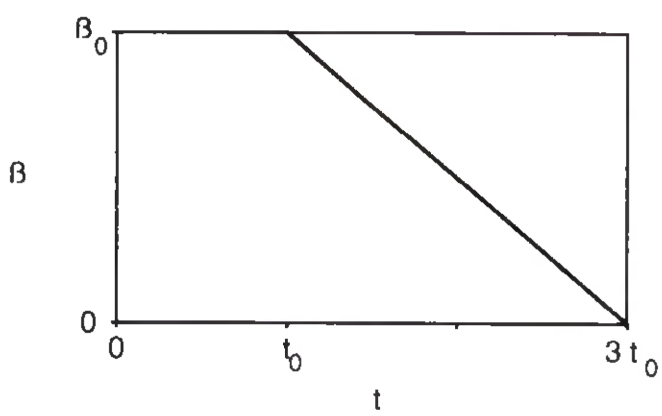

Figure 1 Simplified relationship between charring rate and time

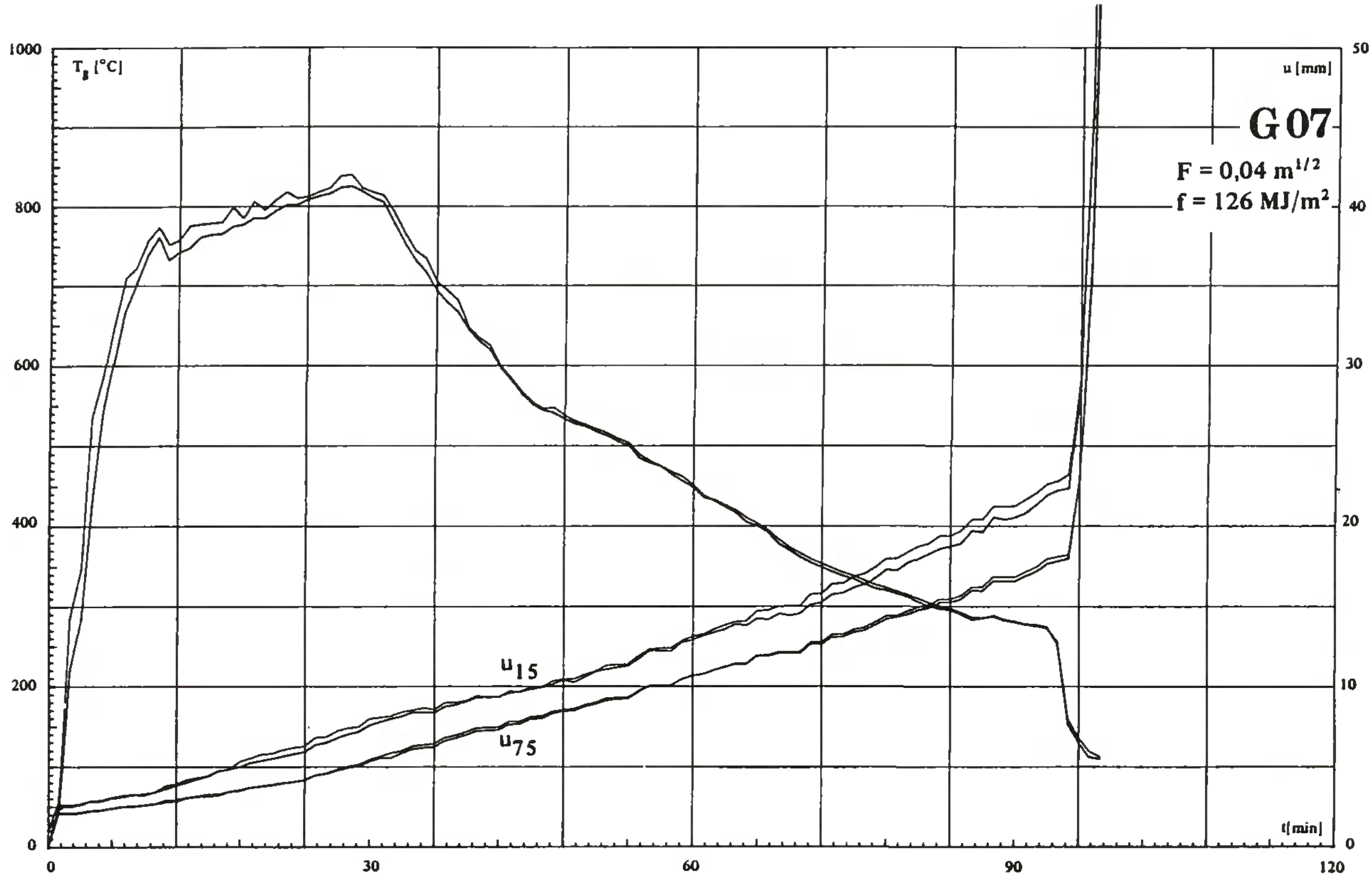

Figure 2 Gas temperature in the furnace and deflection of the test beams versus time

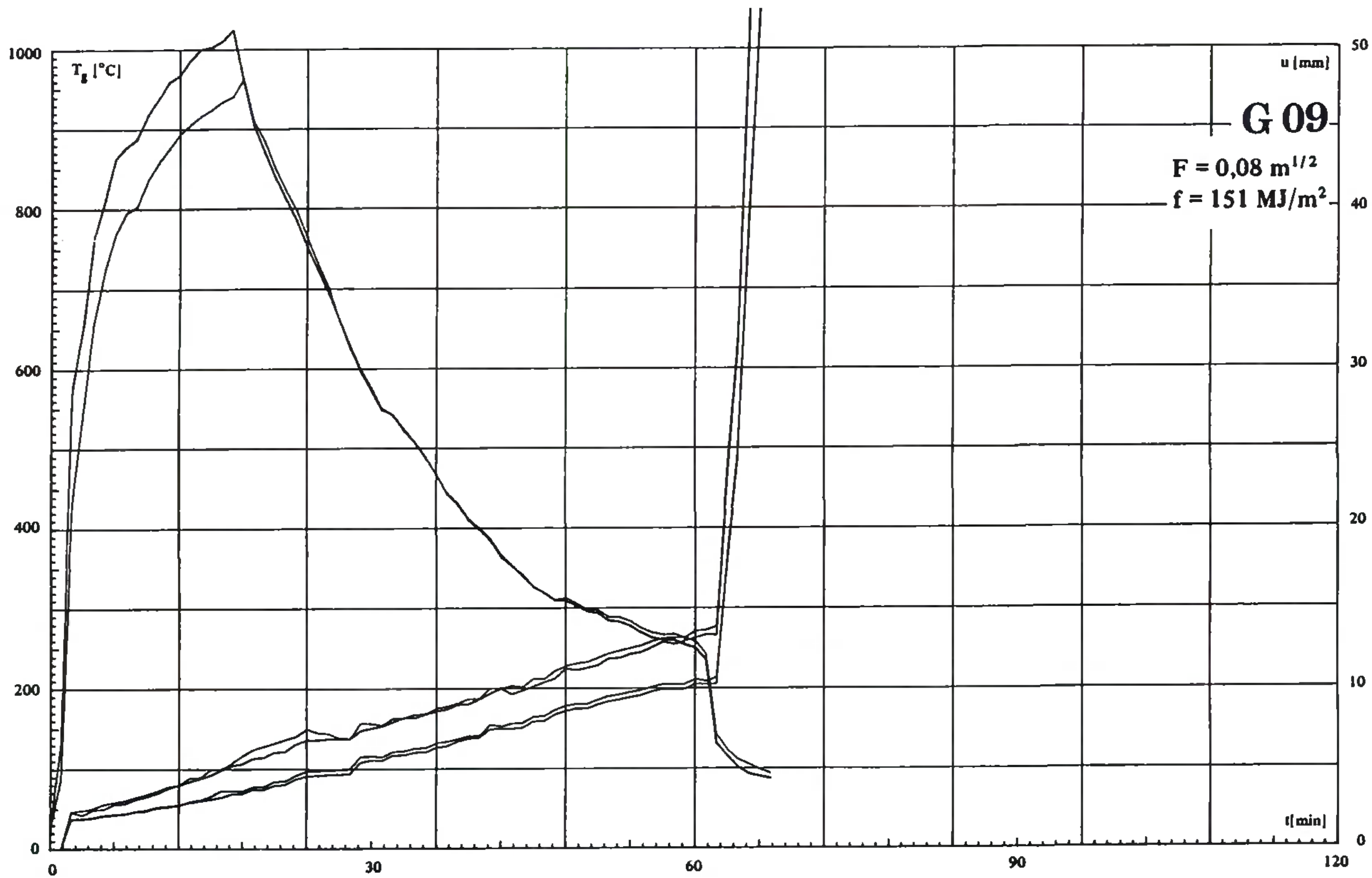

Figure 3 Gas temperature in the furnace and deflection of the test beams versus time

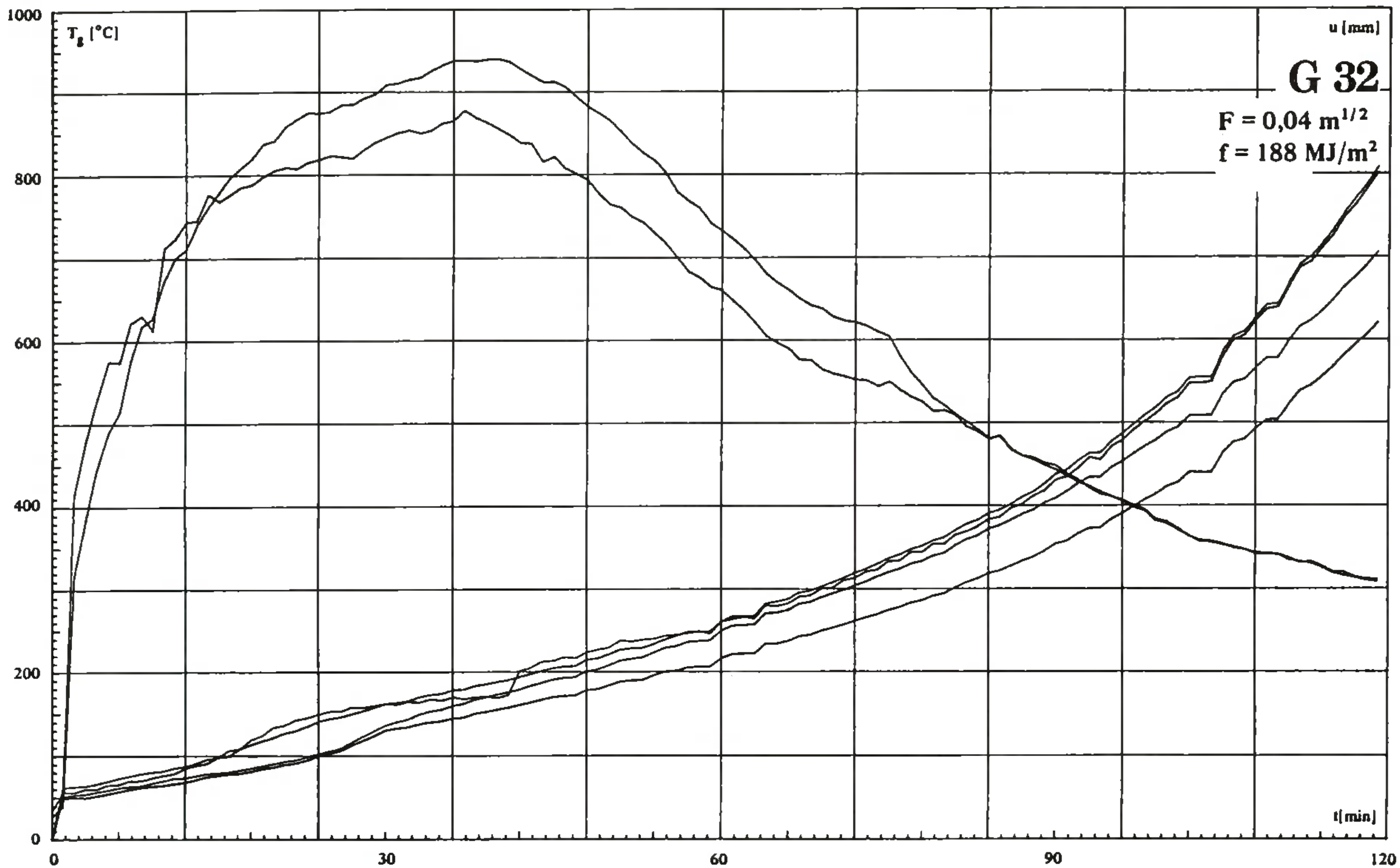

Figure 4 Gas temperature in the furnace and deflection of the test beams versus time

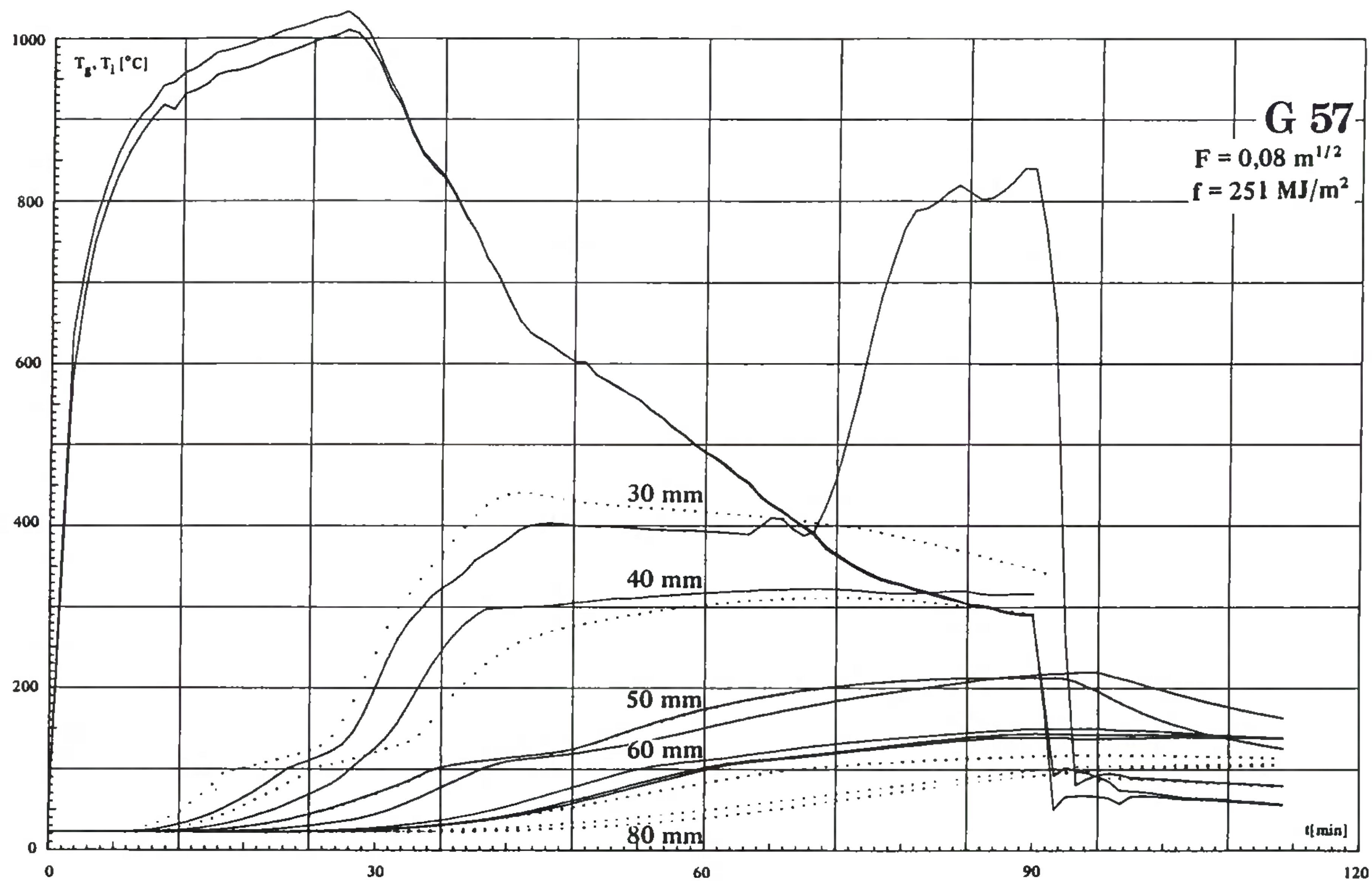

Figure 5 Temperature versus time at different distances from initial surface of the wide side of specimen G 57

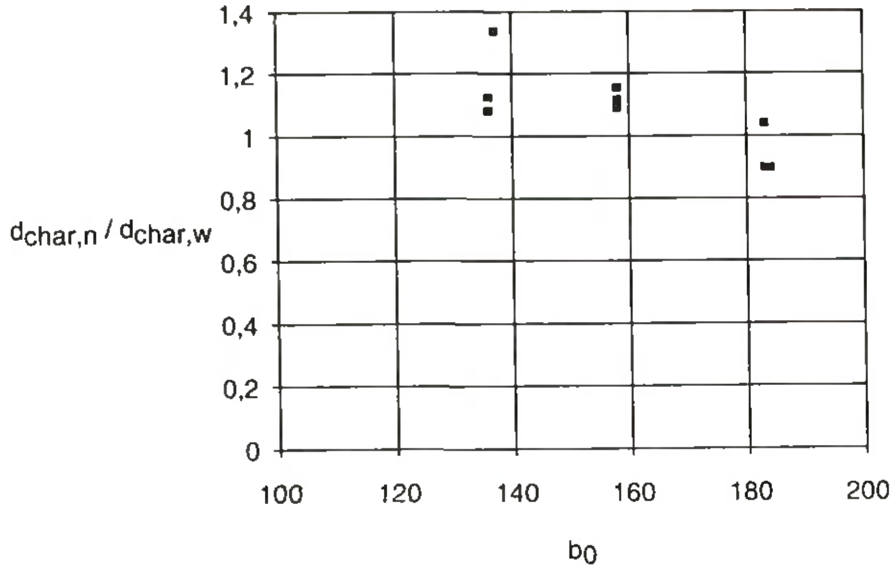

Figure 6 Ratio of charring depths on narrow and wide side versus initial width of narrow side

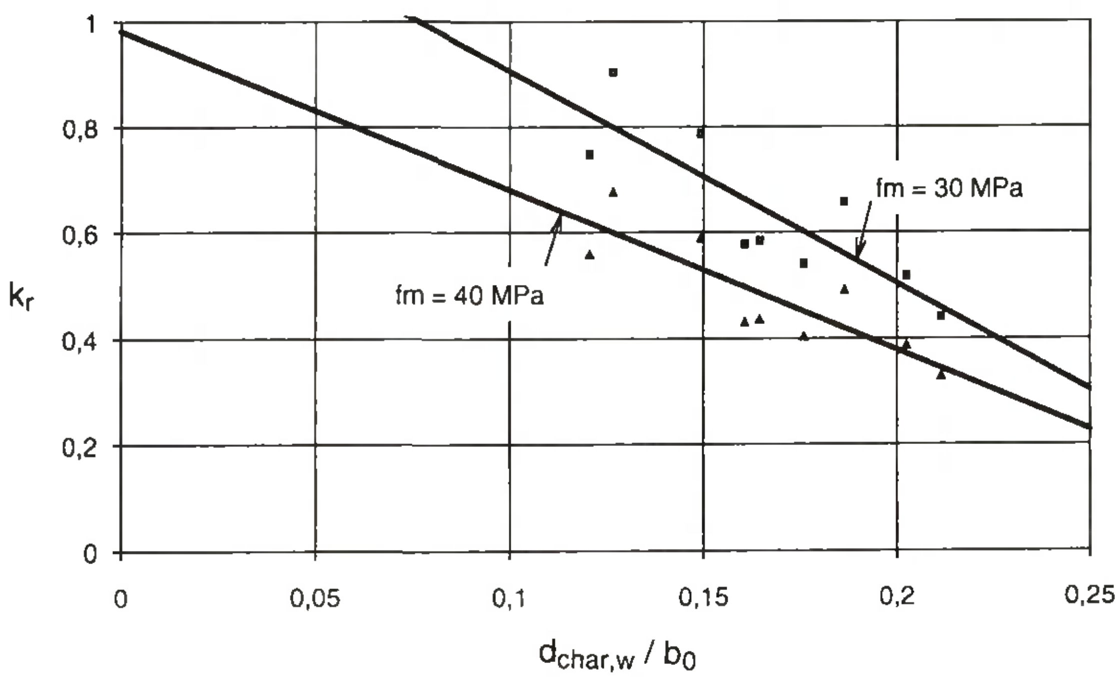

Figure 7 Bending strength ratio of residual cross section versus relative charring depth

SAMMANFATTNING

Denna rapport redovisar bakgrundsmaterial till brandavsnittet av Eurocode 5, Träkonstruktioner (Förslag September 1992) där dimensionering av träkonstruktioner vid fullständiga brandförlopp kommer att ingå. Brandförsök genomfördes vid Aalborg Universitetscenter där belastade limträbalkar utsattes för fullständiga brandförlopp som inkluderar även avsvalningsfasen. Den tresidiga brandexponeringen styrdes medelst ett samband mellan temperatur och tid enligt en energibalansmetod (öppningsfaktormetoden) med olika brandbelastningar och öppningsfaktorer. Provningsresultaten bekräftade tidigare resultat om förkolningshastigheter framtagna av Hadvig. På provkropparnas undre smala sida var medelinbränningsdjupet större än på den breda sidan när den smala sidans bredd var mindre än ungefär 180 mm. Beträffande de mekaniska egenskaperna observerades en minskning av hållfastheten och styvheten av det kvarvarande tvärsnittet, och att denna minskning fortsatte under avsvalningsperioden på grund av kontinuerligt värmeflöde till tvärsnittets inre.

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