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PREFACE

The present report contains the preliminary test results of a number of experimental investigations into the charring, load-bearing and deformation properties of loaded glued laminated beams exposed to parametric fire.

The full-scale tests performed are the first stage in a more extensive theoretical and experimental investigation of the performance of glued laminated structures subject to fire exposure. The test results are published separately in the present form without explanation of the analytical treatment of the problem because several parties have expressed interest in being informed of the preliminary test results and the test methods, especially in connection with the preparatory work in connection with the current Eurocode work.

Aalborg, September 1992

F. Toft Hansen F. Bolonius Olesen

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The following contains a brief report of a number of theoretical and experimental investigations performed at the Department of Building Technology and Structural Engineering at the University of Aalborg. The investigations were performed in 1987 and 1988 for the purpose of setting up and testing applicable methods for a differentiated fire design of glued laminated structures (glulam structures).

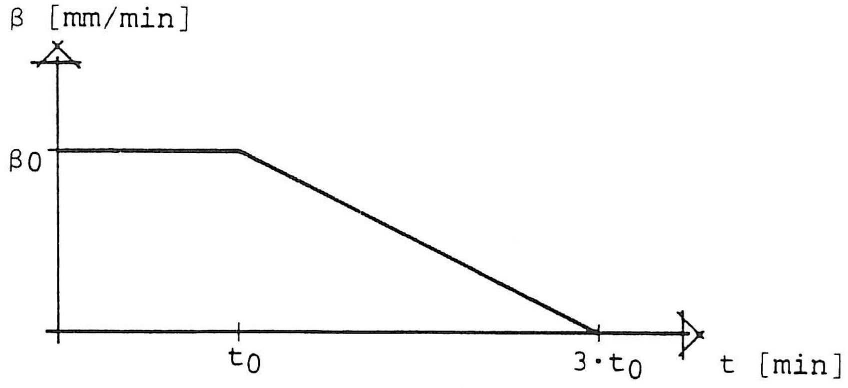
In the Laboratory of Fire Engineering at the Department a number of full-scale tests were performed to investigate the performance of loaded glulam beams during fire exposure, and their correspondence with the models set up for charring of timber, taking account of the reduced strength and stiffness properties of timber at elevated temperatures.

BACKGROUND

So far fire design of load-carrying timber structures has most often been based on rather simplified assumptions with regard to the charring rate, which usually is assumed constant approx. 35 mm/h, i.e. independent of the fire development and the configuration of the structural element. In Svensk Bygg Norm (Swedish Building Code) 1975, however, it is prescribed that for fire compartments with an opening factor > 0.04 $m^{\frac{1}{2}}$ the increased charring rate is taken into account, and correspondingly, the Danish Code for the Structural Use of Timber DS 413 (4th ed. 1982) specifies simplified expressions for the calculation of the dependence of the cross-sectional reduction on the opening factor of the fire compartment and on the fire load density.

The background for these expressions is the analysis of the charring rate for 1-dimensional action (Hadvig, [1]) and the expressions which are based on this for determination of the time-variation of the charring depth dependent on the thermal action.

As a slightly simplified formulation of these expressions for the charring depth the time-variation of the charring rate β can be expressed as follows:



$$\beta_0 = \frac{5 \cdot F - 0{,}04}{4 \cdot F + 0{,}08} \quad \text{[mm/min]} \quad [0{,}02 < F < 0{,}30 \ \mathrm{m}^{\frac{1}{2}}]$$

$$t_0 = 0{,}006 \cdot \frac{q_t}{F} \quad \text{[min]} \quad \left[0 < t_0 \leq \begin{cases} 40 & \text{min} \\ b/(8 \cdot \beta_0) & \text{min} \end{cases}\right]$$

where

F	=	$A \cdot \sqrt{h}/A_t$	$[\mathrm{m}^{\frac{1}{2}}]$
A	=	Sum of area of vertical openings	$[\mathrm{m}^2]$
A_T	=	Total area of surrounding surfaces	$[\mathrm{m}^2]$
h	=	Weighted mean value of opening height	[m]
b	=	Smallest cross-sectional dimension	[mm]
q_t	=	Fire load density	$[\mathrm{MJ/m}^2]$

The expression applies to vertical sides of glulam beams mainly exposed to wooden (fuel) fires.

The strength and stiffness properties of timber at the temperatures that occur in the non-charred part of the structural element during fire exposure have only been sparsely described in the literature. When a better calculation is not available the design is therefore often based on an assumption of unchanged - or almost unchanged - strength and stiffness properties although their reduction is evident. To counterbalance the resulting error (on the unsafe side) Carlsen [2] has suggested that a "weakened zone" should be assumed in the design, where the strength is assumed to decrease linearly from the normal values in the unweakened part of the cross-section (e.g. defined as the areas in which the temperature does not exceed 50 °C) to zero in the char layer. The expressions in DS 413 are based on such simplified assumptions of the extension and significance of the weakened zone.

In the investigations described in the present paper the design model is based on a more differentiated assumption of the temperature independence of the mechanical properties, cf. among other things the investigations made by (Kallioniemi [3]).

EXPERIMENTAL INVESTIGATIONS

So far the test series has included 18 full-scale fire tests performed in the fire chamber/ beam testing machine of the laboratory where the test specimens are exposed to fire on 3 sides (covered on the surface). A further description of the testing equipment is given in [4]. The test specimens are approx. 4 m long in 3 series with the cross-section $h \times b =$

300 × 140 mm (G 05 - G 11)

300 × 160 mm (G 21 - G 26)

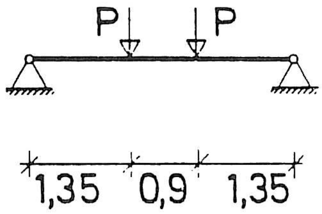
300 × 185 mm (G 31 - G 36)

During the tests *the load* on the test specimens (simply supported with a span of 3.60 m) was kept constant = 2 concentrated loads P of

5.0 kN (G 05 - G 11)

7.0 kN (G 21 - G 26)

8.0 kN (G 31 - G 36)



respectively, for the 3 series. The relatively modest load action has been chosen to prevent stability failure during the tests, since the test specimens were not laterally restrained during this part of the tests.

The thermal action is controlled by a gas temperature-time relation calculated by an energy balance method (the opening factor method) using the following fictitious opening factors and fire loads:

opening factor F ($m^{\frac{1}{2}}$):	0.04	0.06	0.08		
fire exposure q_t (MJ/m^2):	113	126	151	188	251

combined to a total of 6 different fire developments. In each test the fire exposure was momentarily discontinued by spraying with water at the time when the temperature of the fire chamber was approx. 300 °C during the cooling down phase, corresponding to maximum charring being obtained at the same time as the weakened cross-section.

The temperatures in the test specimens were measured by drilled-in thermo elements and were recorded continuously during the tests. For technical reasons during the tests, however, these measurings are performed separately on special test specimens (G 45-57, a total of 14 test specimens) of identical geometry, moisture content etc. and exposed to the same thermal action as during the full-scale tests.

The deflections u_{15} and u_{75} at 4 points (150 and 750 mm, respectively, from the centre point of the beams) have been continuously recorded during the tests.

The failure load for each individual test specimen has been determined by loading till failure immediately (max. 1 min.) after the thermal action was discontinued. For this determination the test specimens were laterally supported at the surface to avoid stability failure.

The charring depth has been determined by manual measuring of the test specimens at approx. 20 gauge points on the underside and the vertical sides prior to testing and subsequent to brushing after the tests.

TEST RESULTS

A survey of the test results is given in table 1. The survey does not contain information of the bending strength of the structural material, since no such measurements have been made. However, it may be assumed that the glulam applied (L30) has a bending strength of approx. 40 MPa. The stiffness parameters of the structural material, on the other hand, were examined prior to the fire tests.

The survey comprises the following data for each individual test specimen:

- Geometrical cross-section prior to testing
- Geometrical cross-section subsequent to testing
- Mean charring depth x_s on the vertical sides
- Mean charring depth x_b on the underside
- E-modulus prior to the fire test
- G-modulus prior to the fire test
- Thermal fire load (fire load and opening factor)
- Mechanical load
- Failure load

The figures 2-9 show the development of the deflections u_{15} and u_{75} for 16 full-scale tests, and figure 10 shows examples of print-outs of temperature measurements from the supplementary tests G 45 - 57.

In figure 1 the measured values of the mean charring depths on the vertical beam sides with the corresponding calculated values are inserted.

CONCLUSIONS

From the test results the following preliminary conclusion can be drawn:

- For all tests a good agreement between measured and calculated values of the mean charring depths on the vertical sides of the beams was ascertained (cf. figure 1).
- In most cases, but not all, the charring depths on the underside exceed those on the vertical sides (by 15% on average).
- In all cases the measured deflections are significantly larger than the values which can be calculated based on theories or design rules known so far (including DS and SBN), which disregard creep phenomena.
- In all cases the measured failure loads are lower than the values calculated from design rules known so far (including DS and SBN).

LITERATURE

[1] Hadvig, S.: *Charring of Wood in Building Fires.* University of Denmark, Lyngby, 1981.

[2] Carlsen, B.-E.: *Brandteknisk dimensionering af bærende trækonstruktioner* (in Danish). Nordisk Trätidsskrift, hæfte 6, Aalborg, 1979.

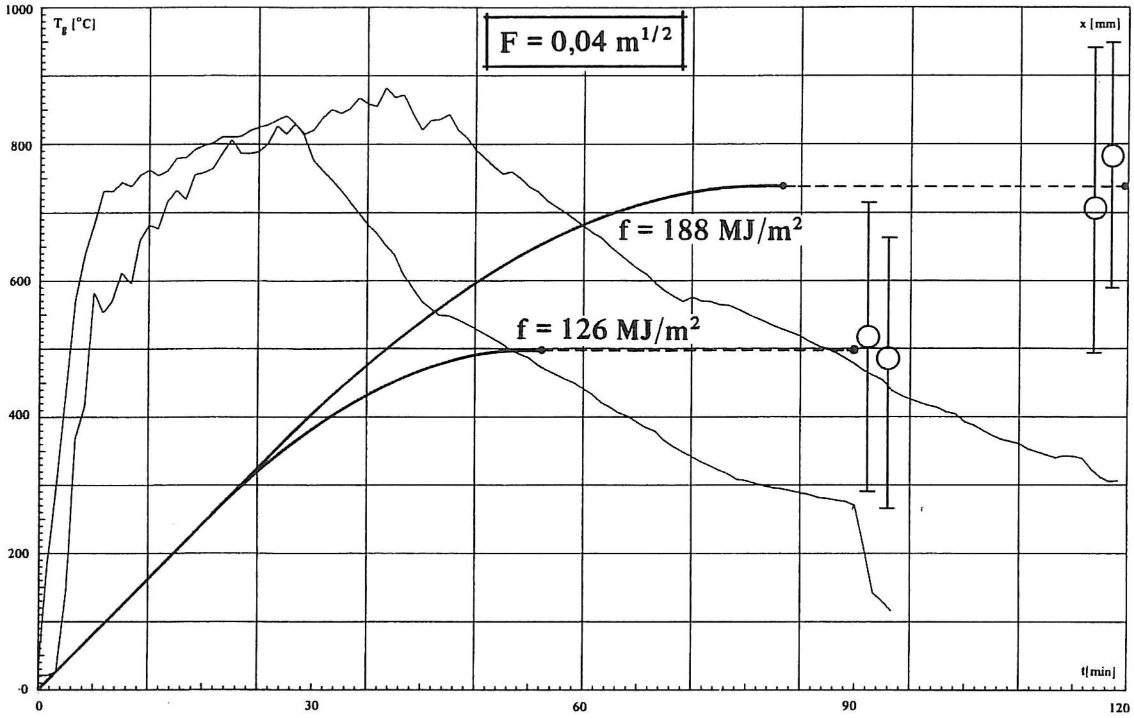
[3] Kallioniemi, P.: *The Strength of Wood Structures During Fires.* VTT Symposium 9, Espoo, 1980.

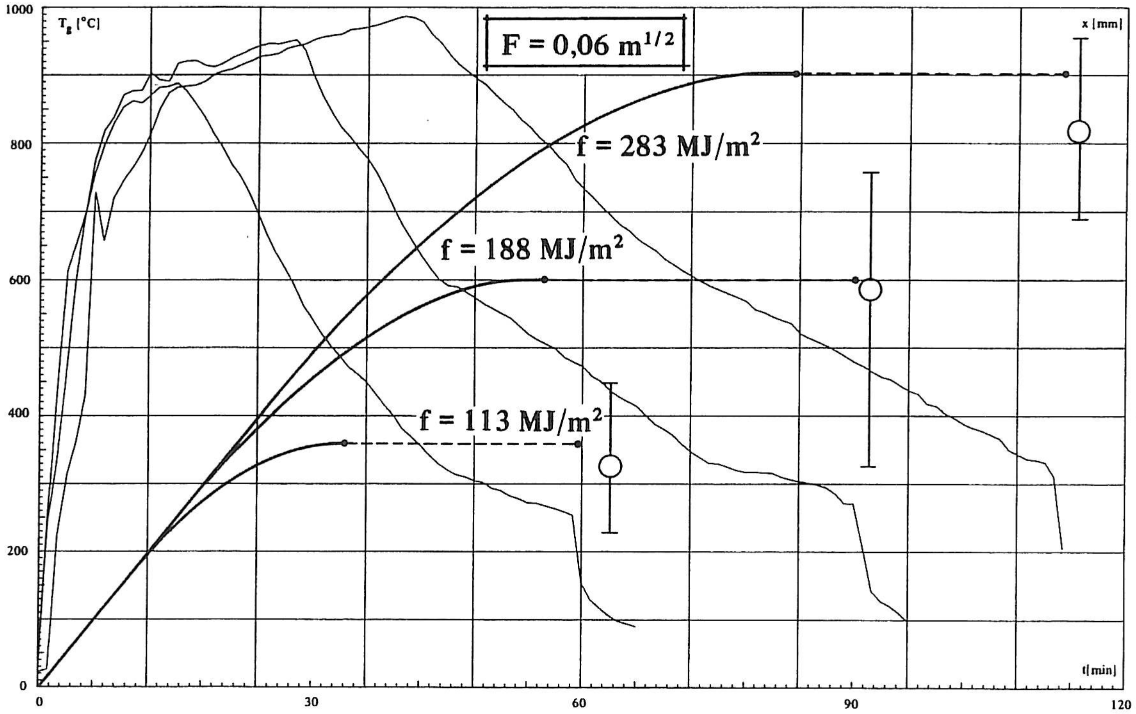
[4] Hviid, N. J. & F. B. Olesen: *Testing Facilities at the AUC Fire Research Laboratory.* Department of Building Technology and Structural Engineering, University of Aalborg. Report no. 7801, Aalborg, 1978.

No.	$h_o \cdot b_o$	E_0	G_0	$x_s^{meas.}$	$x_s^{calc.}$	$x_b^{meas.}$	$h_f \cdot b_f$	F	q_t	P	$P_{ult.}^{meas.}$	$\sigma_{ult.}^{f}$	$3 \cdot t_0$
	mm·mm	MPa	MPa	mm	mm	mm	mm·mm	$m^{\frac{1}{2}}$	MJ/m^2	kN	kN	MPa	min.
G 05	(300·140)	-	-	-	30,7	-	-	0,06	188	5,0	8,3	-	56
G 06	(300·140)	-	-	35,4	37,6	-	-	0,04	188	5,0	-	-	85
G 07	298·137	14 250	550	24,1	25,2	32,2	266·89	0,04	126	5,0	12,6	16,2	57
G 08	296·136	14 800	760	16,4	18,4	17,7	278·103	0,06	113	5,0	22,0	22,4	34
G 09	296·136	16 200	645	20,3	20,4	22,8	273·95	0,08	151	5,0	20,6	23,6	34
G 11	296·136	12 600	650	-	33,9	-	-	0,08	251	5,0	9,6	-	56
G 21	299·159	13 450	778	-	30,7	-	-	0,06	188	7,0	18,1	-	56
G 22	(300·160)	-	-	-	37,6	-	-	0,04	188	7,0	-	-	85
G 23	298·158	12 600	650	26,0	25,2	28,3	270·106	0,04	126	7,0	16,7	17,5	57
G 24	299·157	14 820	724	-	18,4	-	-	0,06	113	7,0	31,5	-	34
G 25	298·158	14 150	678	32,0	33,9	36,9	271·94	0,08	251	7,0	13,2	15,5	56
G 26	299·158	13 380	683	20,0	20,4	22,3	276·118	0,08	151	7,0	30,1	27,1	34
G 31	(300·185)	-	-	-	30,7	-	-	0,06	188	8,0	16,3	-	56
G 32	299·184	14 000	510	38,9	37,6	40,4	259·106	0,04	188	8,0	11,6	13,2	85
G 33	298·183	11 700	600	29,4	30,7	26,4	272·124	0,06	188	8,0	19,6	17,3	56
G 34	297·183	13 800	610	34,1	33,9	30,6	266·115	0,08	251	8,0	19,8	19,7	56
G 35	(300·185)	-	-	-	20,4	-	-	0,08	151	8,0	36,2	-	34
G 36	(300·185)	-	-	40,5	46,0	49,3	-	0,06	283	8,0	10,5	-	85

* N.B.: $\sigma_{ult.}^{f}$ is calculated as a "formal" ultimate bending stress = $M_{ult.}/Z_f = 1.35\ P_{ult.}/Z_f$

Table 1. Review of test results.


F = 0,04 m$^{1/2}$
T_g [°C]
x [mm]
t[min]
f = 188 MJ/m^2
f = 126 MJ/m^2
0
200
400
600
800
1000
0
30
60
90
120
0
10
20
30
40
50


F = 0,06 m$^{1/2}$
T_g [°C]
x [mm]
t[min]
f = 283 MJ/m^2
f = 188 MJ/m^2
f = 113 MJ/m^2
0
200
400
600
800
1000
0
30
60
90
120
0
10
20
30
40
50

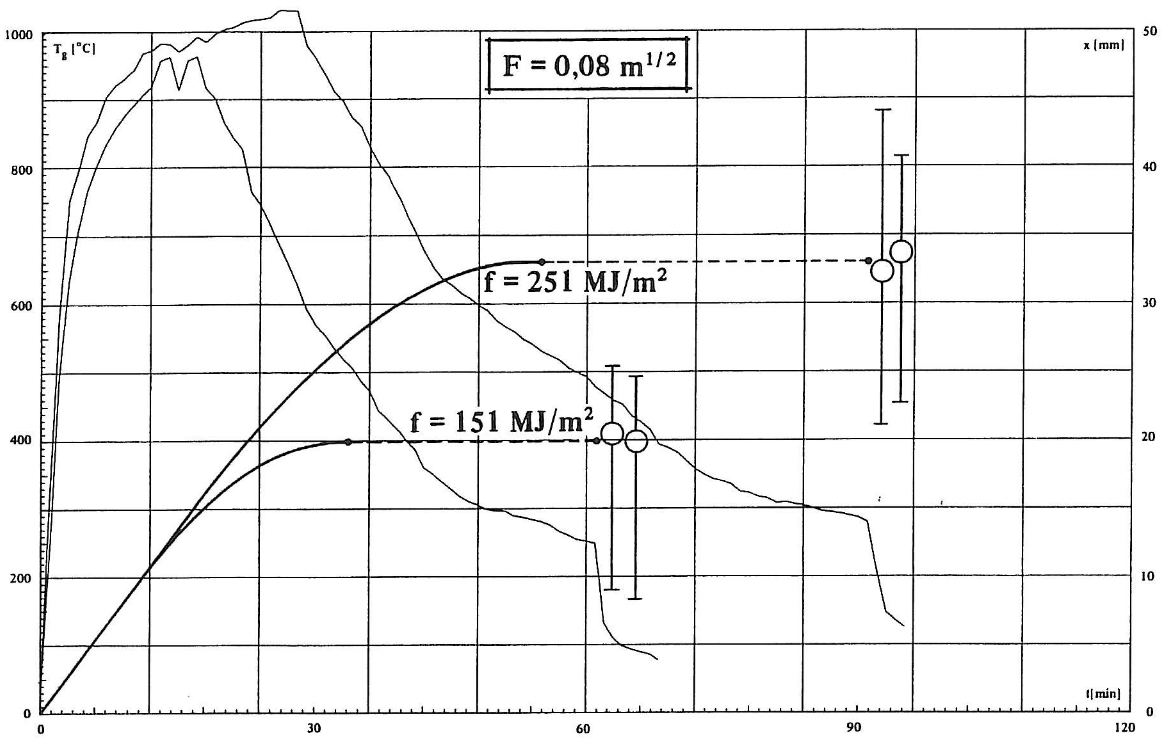
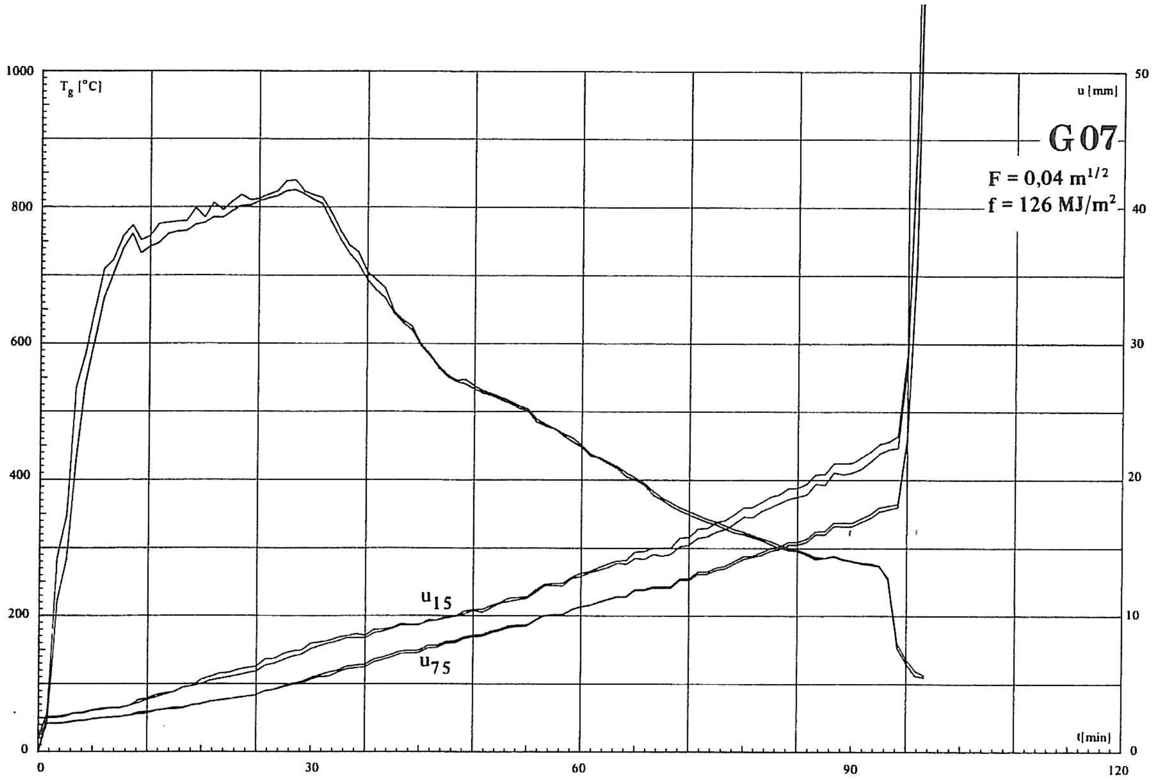


Figure 1. The measured values of the mean charring depths on the vertical beam sides are shown by ϕ.
For comparison are shown the corresponding calculated values as indicated at page 2.



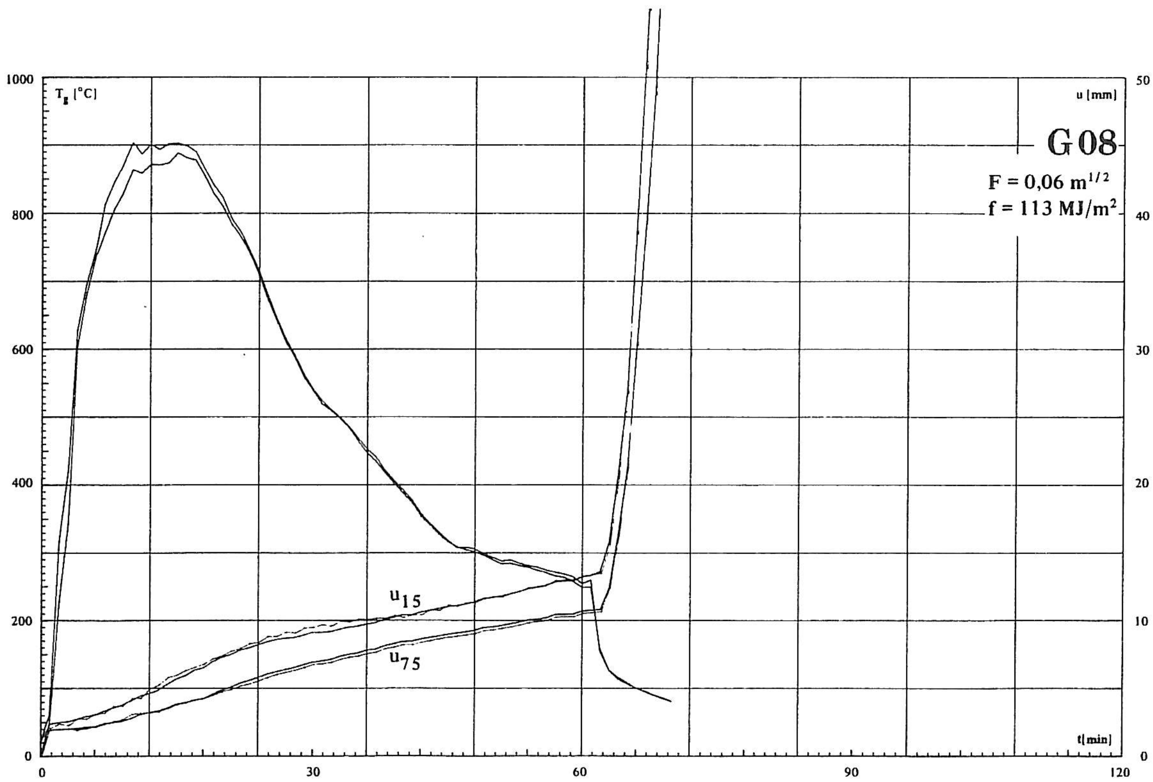


Figure 2. Deflections u_{15} and u_{75} for G 07 and G 08.

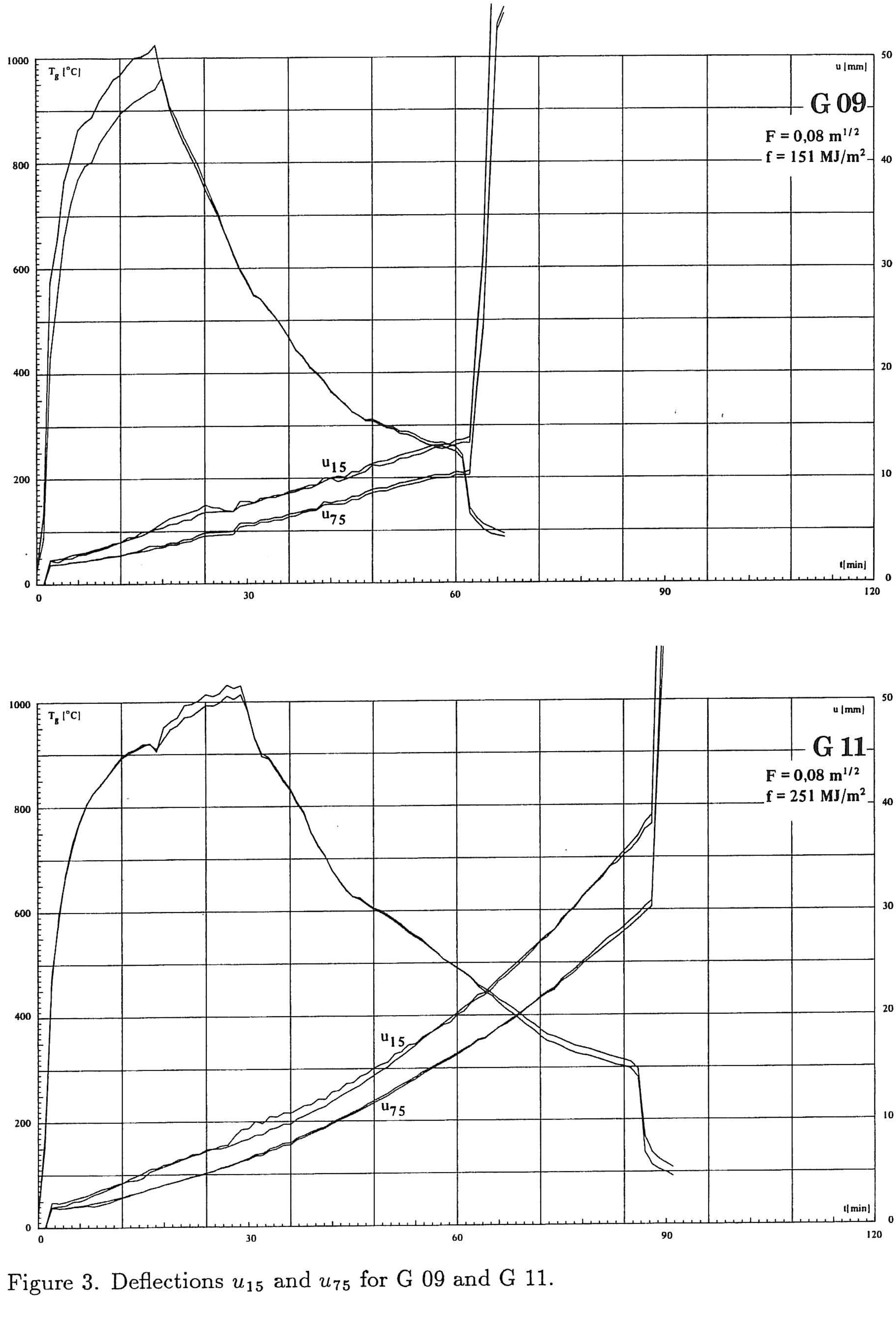


Figure 3. Deflections u_{15} and u_{75} for G 09 and G 11.

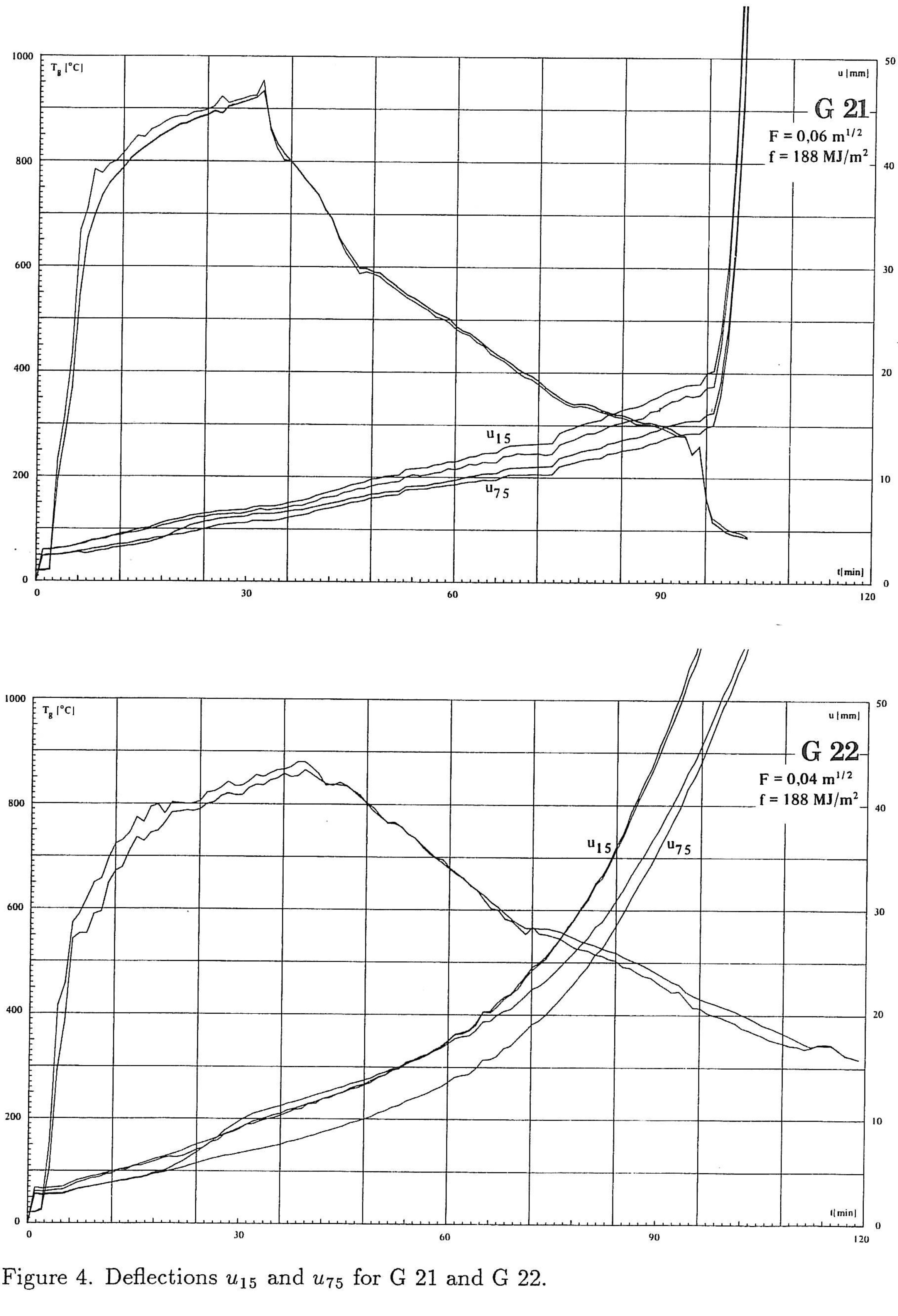


Figure 4. Deflections u_{15} and u_{75} for G 21 and G 22.

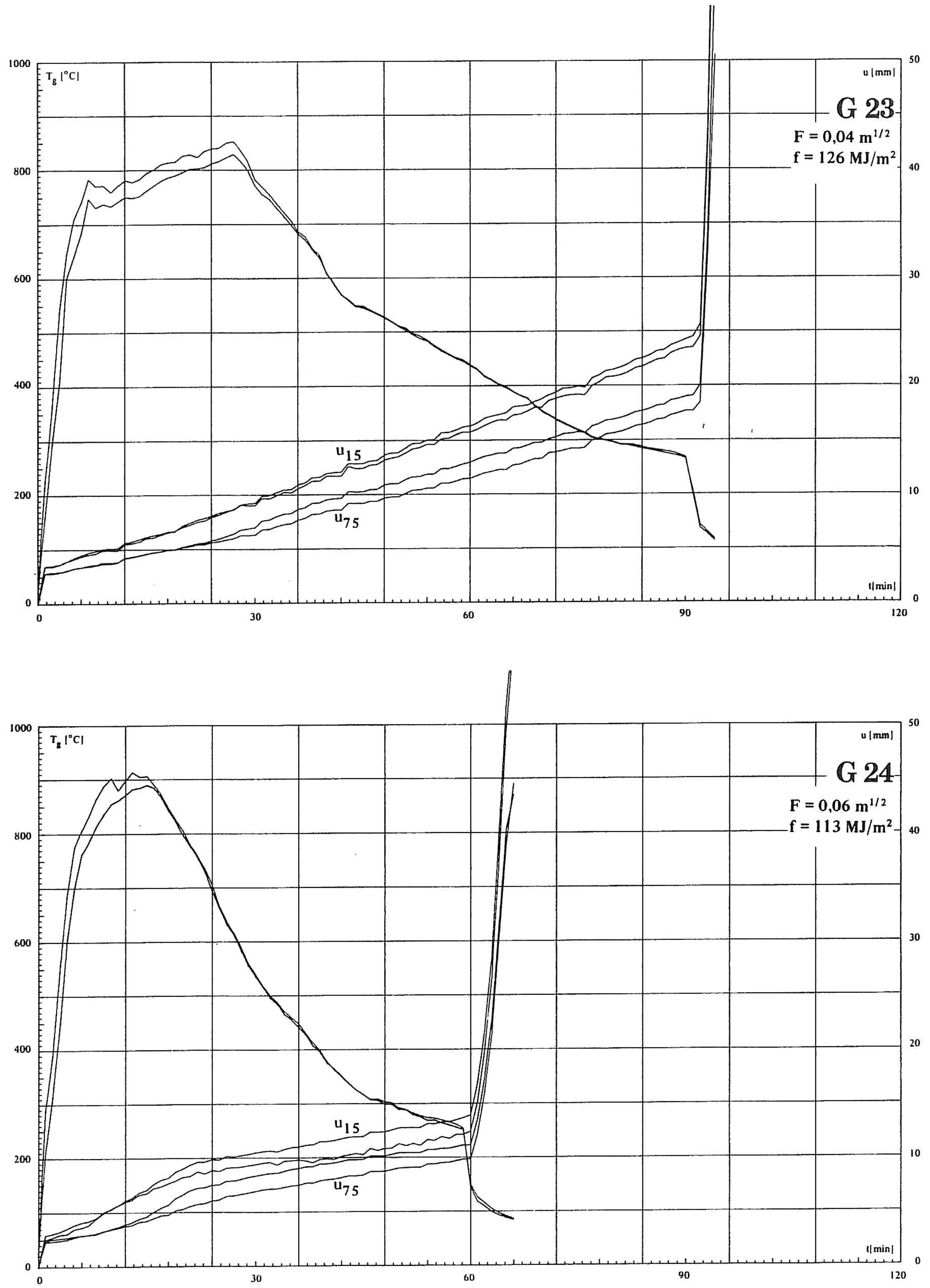
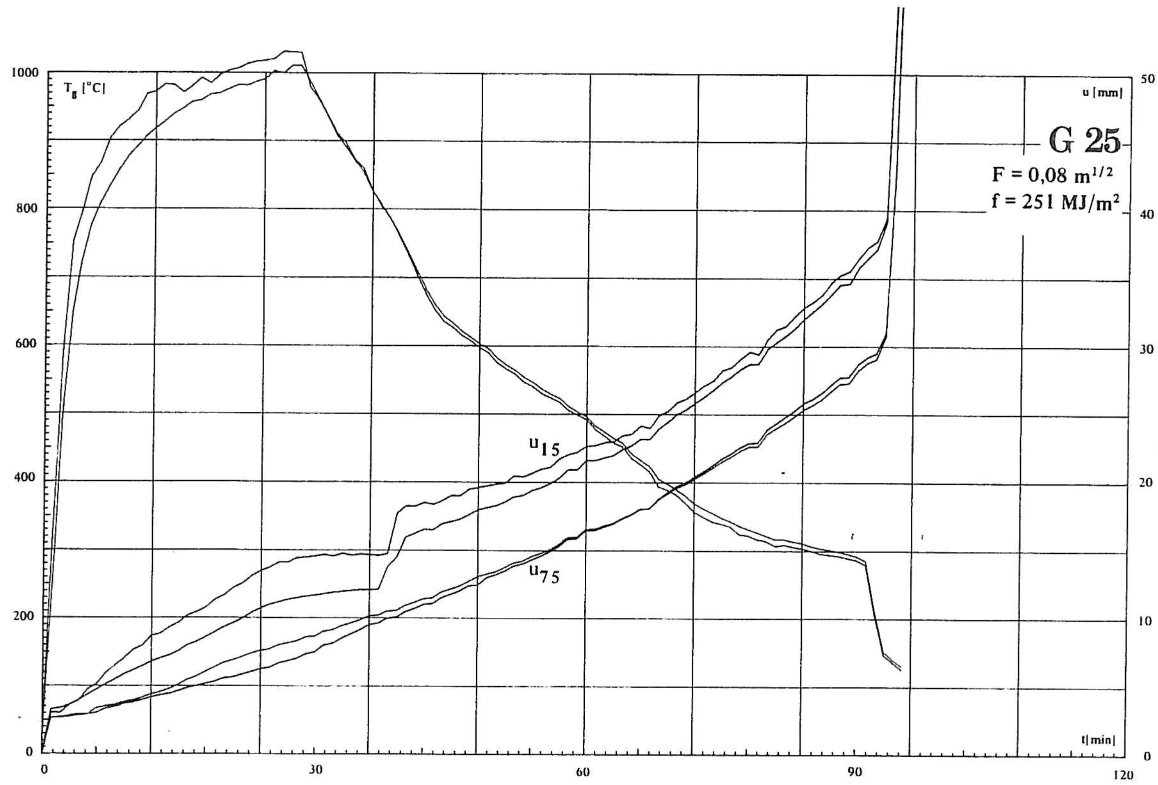


Figure 5. Deflections u_{15} and u_{75} for G 23 and G 24.



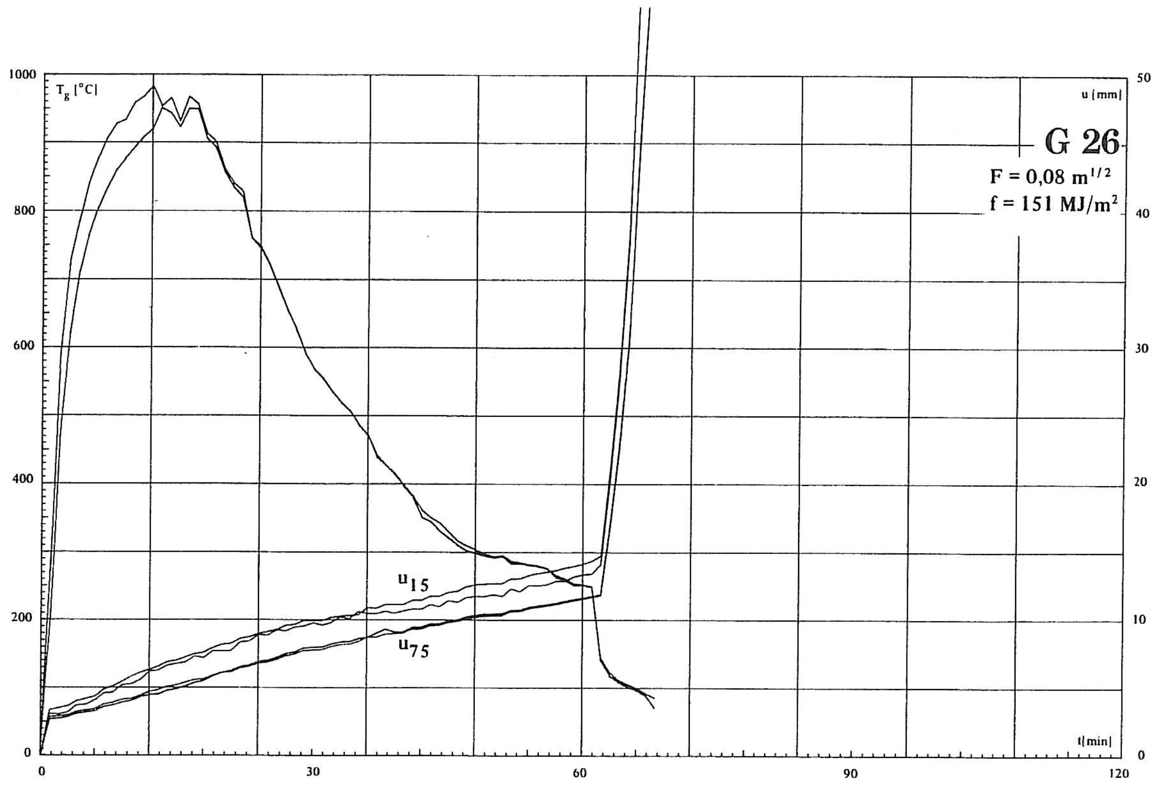
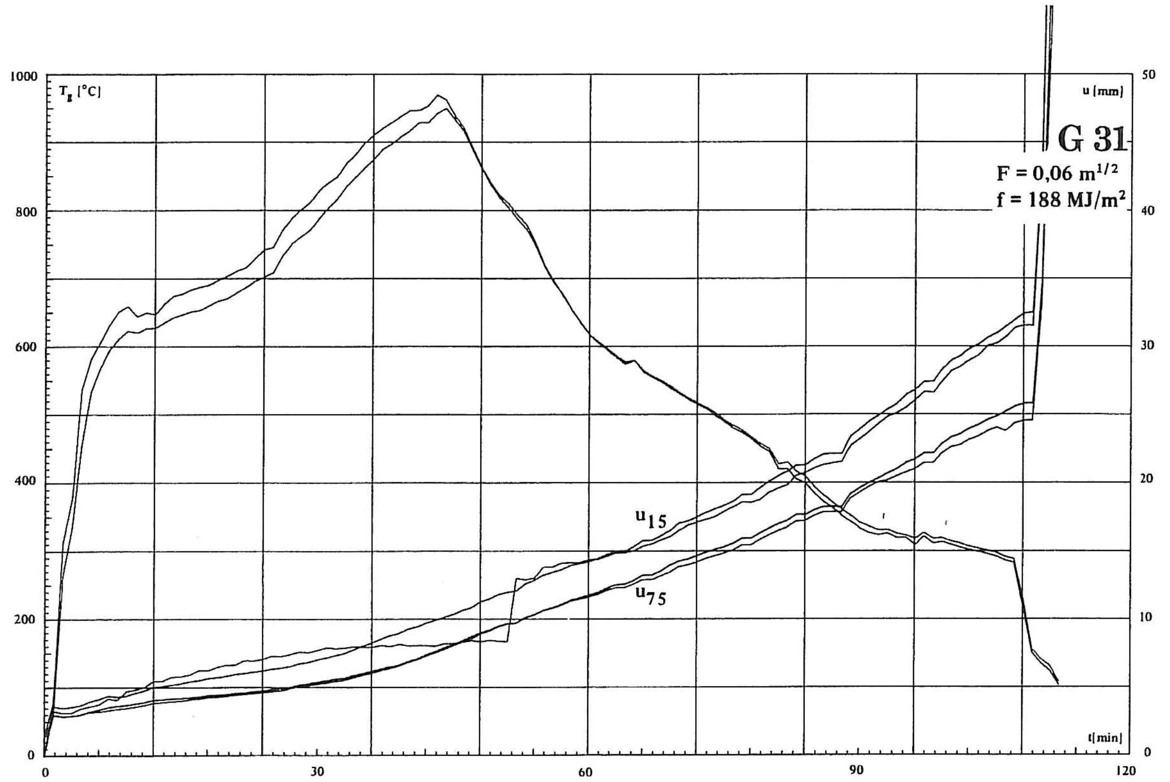


Figure 6. Deflections u_{15} and u_{75} for G 25 and G 26.



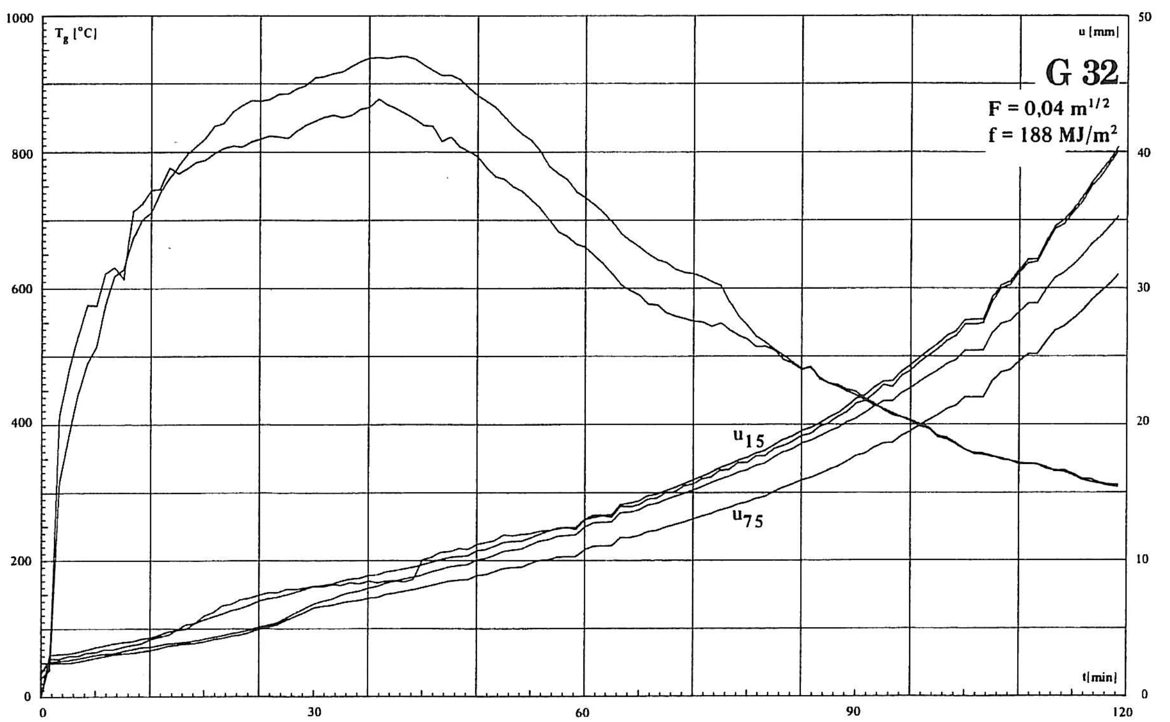
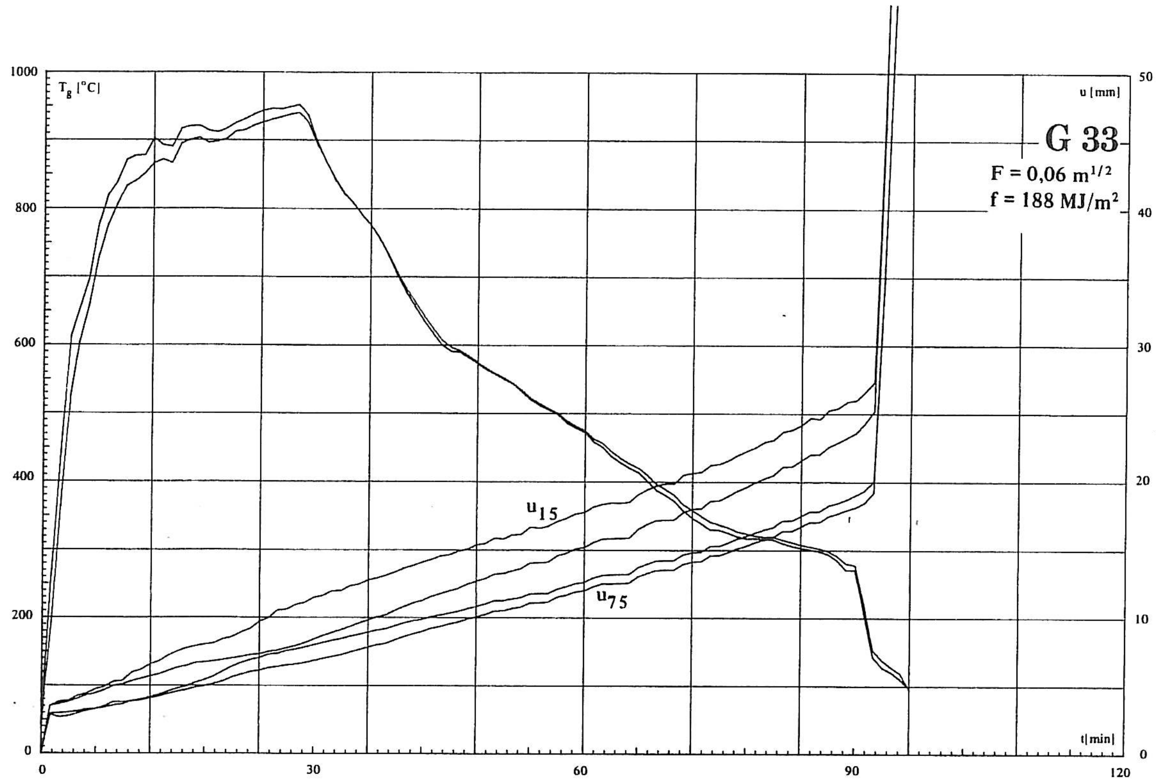


Figure 7. Deflections u_{15} and u_{75} for G 31 and G 32.



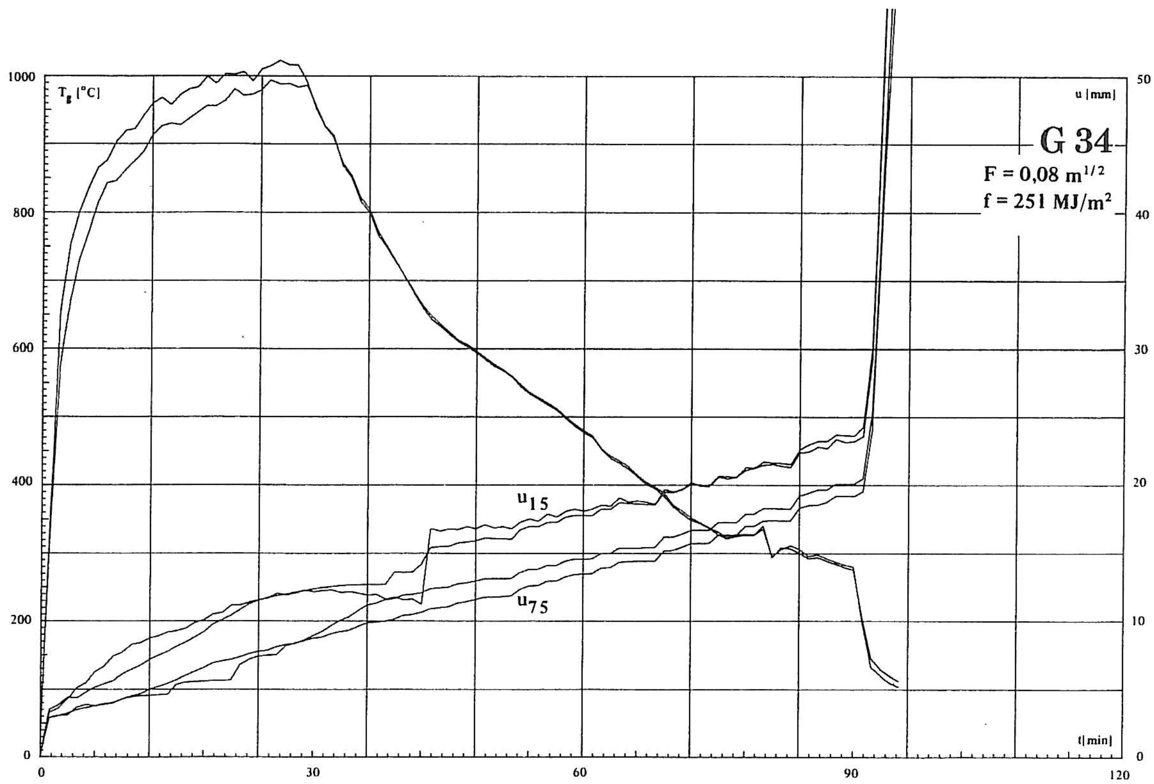
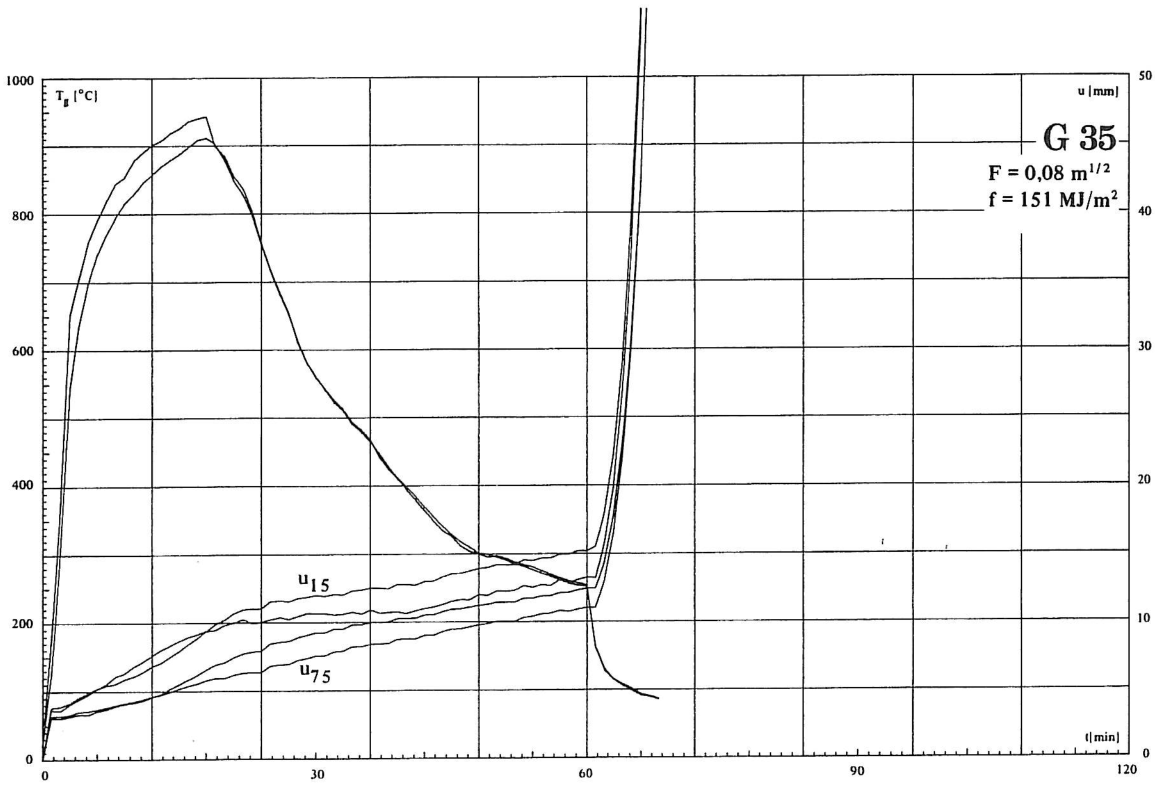


Figure 8. Deflections u_{15} and u_{75} for G 33 and G 34.



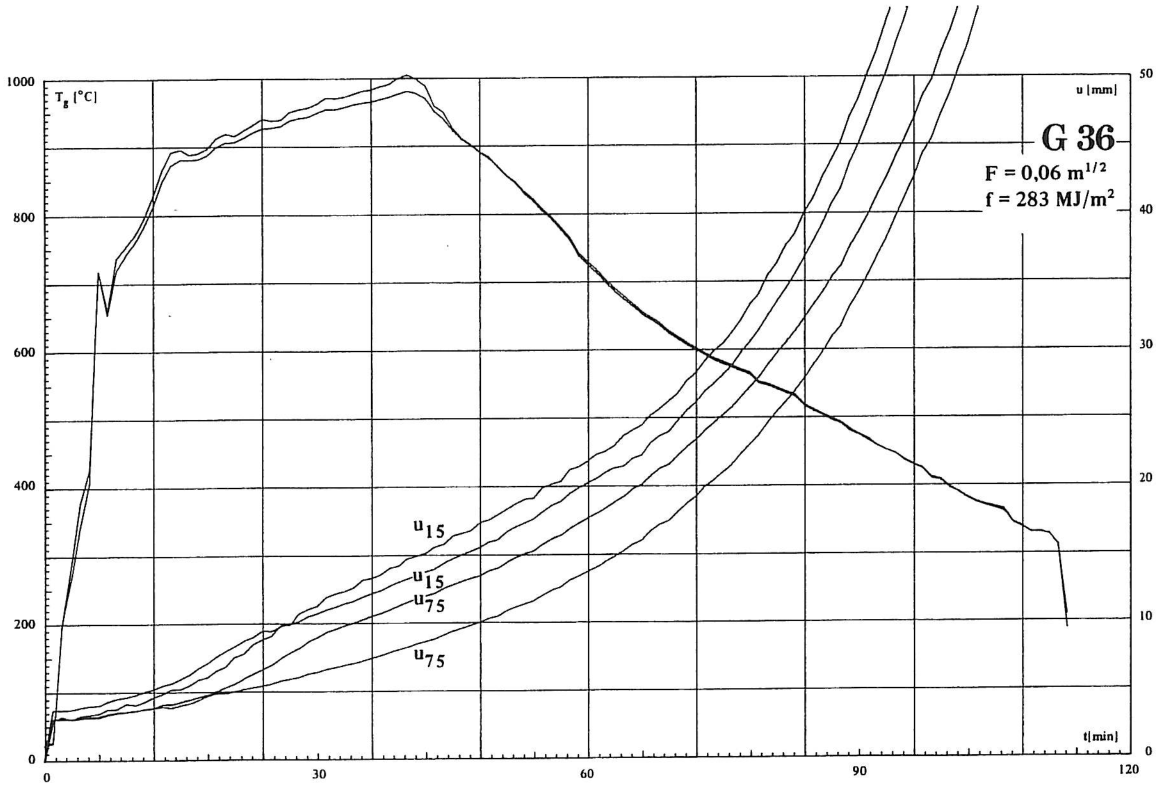
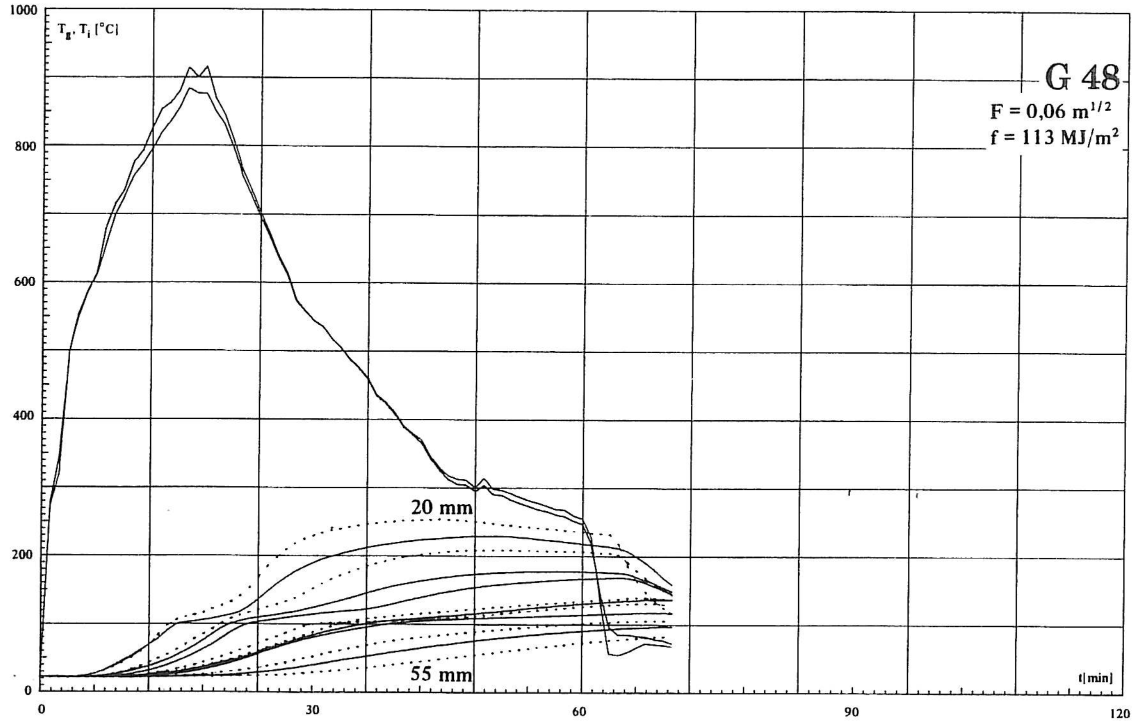
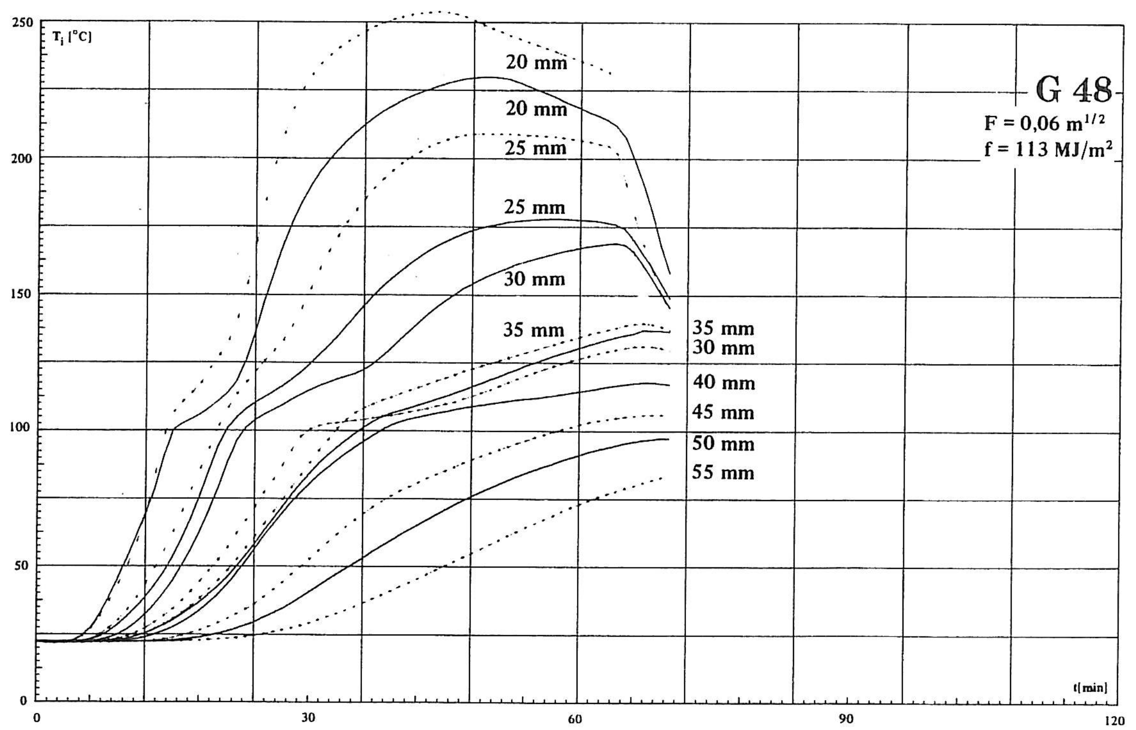


Figure 9. Deflections u_{15} and u_{75} for G 35 and G 36.


Tg, Ti [°C]
G 48
F = 0,06 m^1/2
f = 113 MJ/m²
20 mm
55 mm
t[min]
1000
800
600
400
200
0
30
60
90
120


Ti [°C]
G 48
F = 0,06 m^1/2
f = 113 MJ/m²
20 mm
20 mm
25 mm
25 mm
30 mm
35 mm
35 mm
30 mm
40 mm
45 mm
50 mm
55 mm
t[min]
250
200
150
100
50
0
30
60
90
120

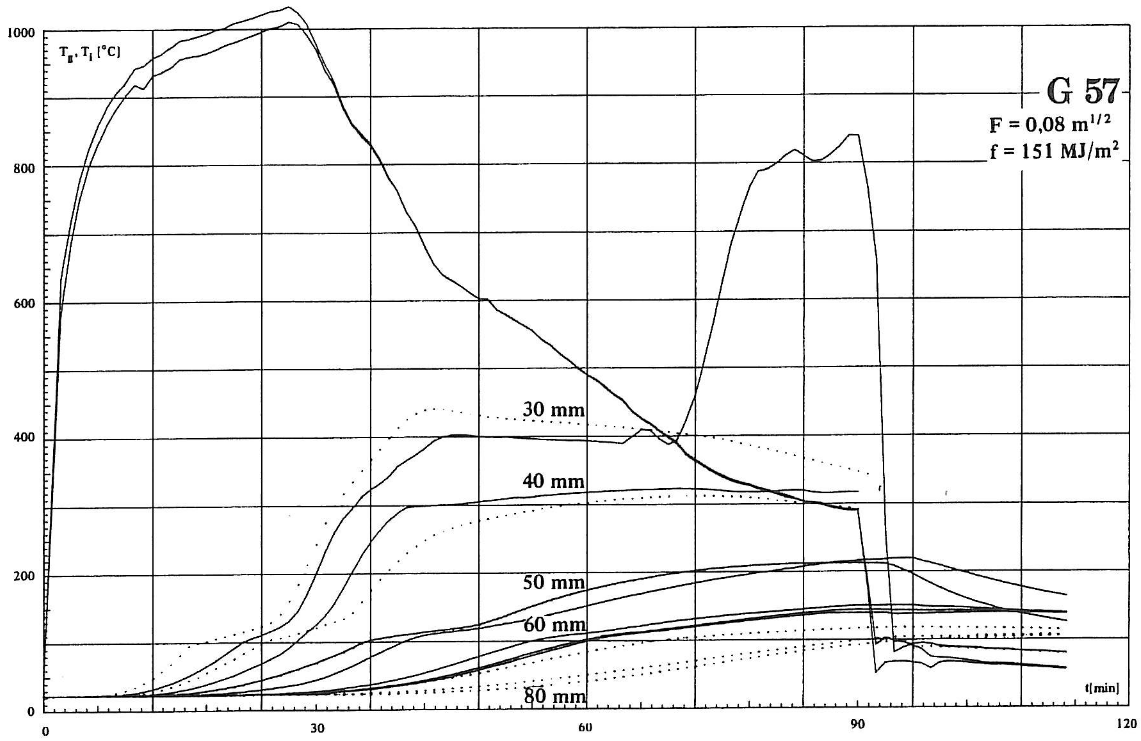


Figure 10. Internal temperatures for specimens G 48 and G 57 (measured values).