REPORT

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Connections of sandwich panels

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Symbols and notations

C	stiffness of clamping of fastener in the substructure
D	thickness of panel; distance between substructure and washer
EI	bending stiffness
F	force
F_F	force at the face sheet (elongated hole)
F_{Rk}	characteristic load bearing capacity
d	nominal diameter of a fastener
d_1	minor diameter of the threaded part of a fastener
d_S	diameter of unthreaded shank of the fastener
f	displacement
f_u	tensile strength
k_F	stiffness of a face sheet (elongated hole)
k_v	stiffness of a fastening
t	thickness of a steel sheet
t_{sup}	thickness of substructure
t_{F1}	thickness of the external face sheet
t_{F2}	thickness of the internal face sheet
w	deflection

1 Preliminary remarks

The load bearing capacity of fastenings of sandwich panels is usually determined by testing and it is given in (national) approvals – e.g. in the German approval Z-14.4-407 [22]. For the design of shear diaphragms made of sandwich panels, in addition to the load bearing capacity also the stiffness of the fastenings has to be known [2]. As the load bearing capacity, also the stiffness of a fastening can be determined by testing. But in the common approvals there are not any specifications of the stiffness of fastenings.

At the moment for both, load bearing capacity and stiffness of fastenings of sandwich panels, no general calculation procedure exists. For each single case experimental tests are necessary.

Within the framework of task 3.3 of the EASIE project shear diaphragms made of sandwich panels have been investigated [2]. For the stiffness of a shear diaphragm the stiffness of the connections is decisive. Therefore especially fastenings of sandwich panels have been investigated within the framework of task 3.3. The experimental tests on fastenings of sandwich panels are documented in deliverable D3.2 – part 2 [1]. In the report at hand the evaluation of the tests is presented. Calculation procedures for determination of load bearing capacity and stiffness of fastenings of sandwich panels are developed.

2 Fastenings of sandwich panels

Sandwich panels are screwed through the external face sheet to the substructure. The head of the screw and the washer lie on the external face sheet separated from the substructure by the core layer (Fig. 2.1).

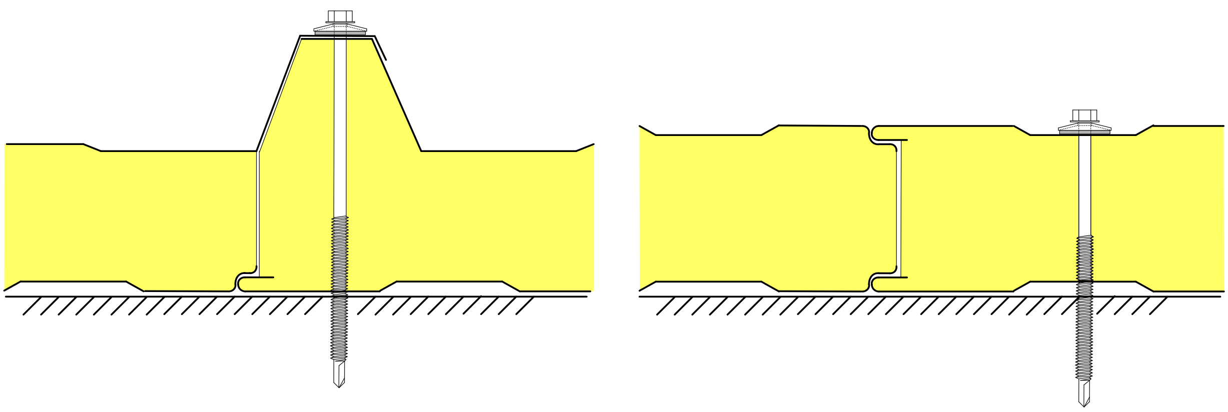
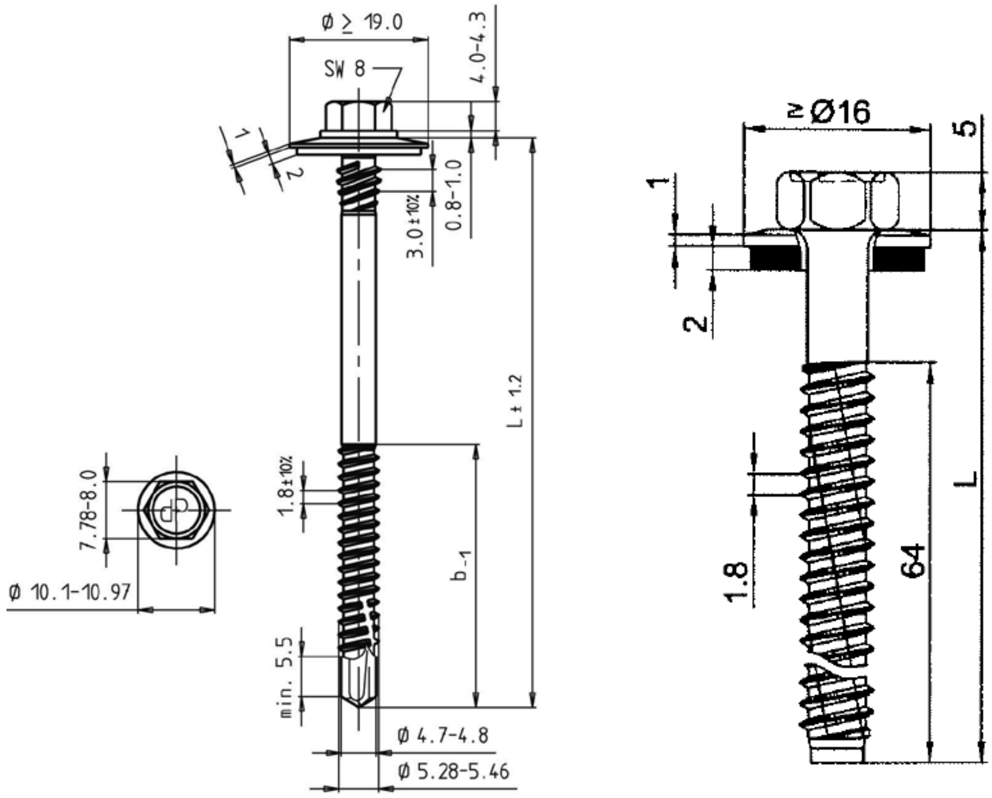


Fig. 2.1: Connections of sandwich panels to the substructure

For the connections of sandwich panels to a (steel) substructure usually self-drilling or self-tapping screws made of stainless steel are used. The fasteners have a nominal diameter of 5,5 mm to 8,0 mm (Fig. 2.2). The screw fasteners often have an additional support thread under the head. To get rainproof connections sealing washers with a nominal diameter of approximately 16 mm to 22 mm are used. The sealing washers also increase the resistance against pull-through failure.



self-drilling screw *self-tapping screw*

Fig. 2.2: **Screw fasteners for fastenings of sandwich panels to substructures**

At the longitudinal joints of roof panels also the external face sheets are connected (Fig. 2.3), whereas this connection mainly contributes to the water tightness and the stabilisation of the large free leg. For determination of the stiffness of shear diaphragms the stiffness of these connections can also be taken into account. Therefore this kind of fastening was also investigated within the framework of task 3.3 of the EASIE project.

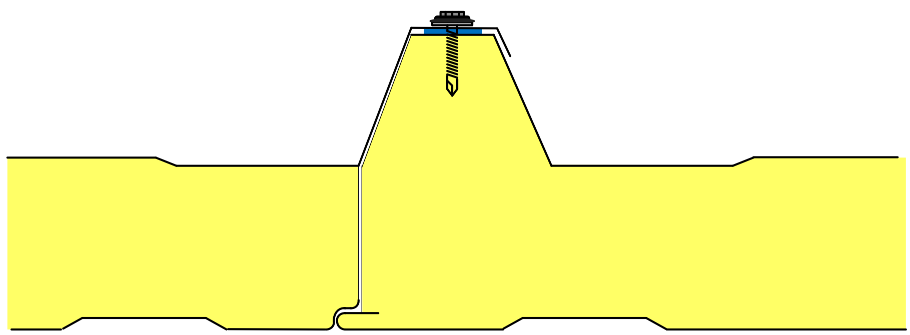


Fig. 2.3: **Fastenings of longitudinal joints**

Usually for the connection of the external face sheets at longitudinal joints self-drilling screws with nominal diameter 4,8 mm to 6,3 mm are used (Fig. 2.4). To get rainproof and airtight joints sealing washers and often also sealing tapes are used.

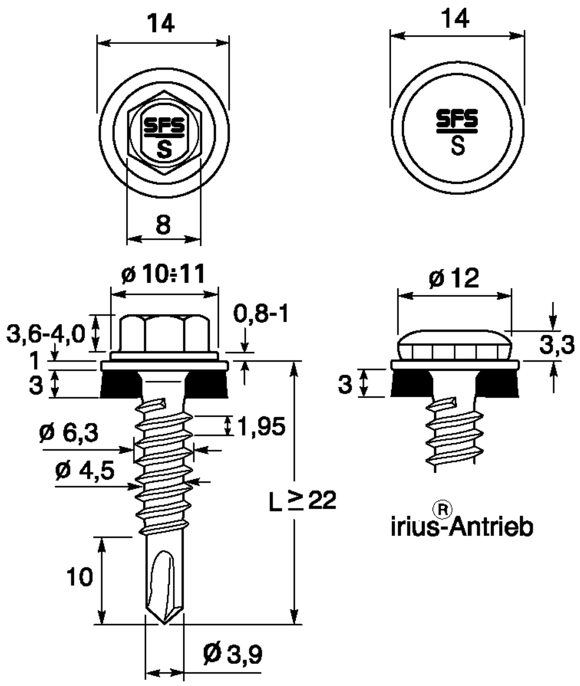


Fig. 2.4: Self-drilling screw for fastenings of longitudinal joints

In deliverable D3.3 – part 3 connections of sandwich panels and steel substructures are investigated. Sandwich panels with a thickness D (distance between internal and external face at point of fastening) of 40 mm to 200 mm and steel faces with a thickness of 0,40 mm to 1,00 mm are considered. As substructure steel with a thickness of 1,5 mm to 10,0 mm is assumed. As fasteners self-drilling and self-tapping screws made of stainless steel with nominal diameters of 5,5 mm to 8,0 mm are considered.
In addition fastenings at longitudinal joints of roof panels are investigated (section 6). For these fastenings self-drilling screws with nominal diameter 4,8 mm to 6,3 mm are assumed.

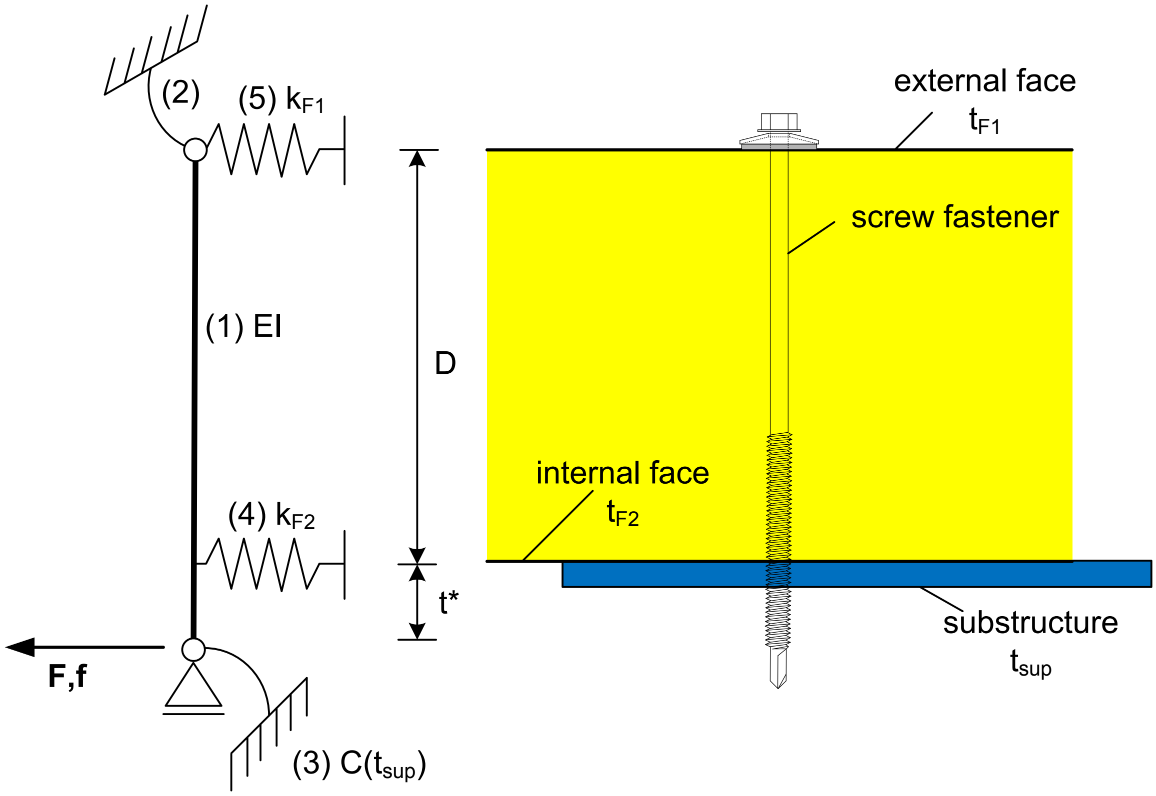
3 Single components of a fastening

The stiffness of a fastening of a sandwich panel to a steel substructure consists of the following single components:

(1) Bending stiffness EI of the fastener
(2) Clamping of the head of the fastener (rotational spring)
(3) Clamping of the fastener in the substructure (rotational spring with stiffness C)
(4) Hole elongation of the internal face sheet (longitudinal spring with stiffness k_{F2})

(5) Hole elongation of the external face sheet (longitudinal spring with stiffness k_{F1})

A fastening with its single components is shown in Fig. 3.1.



t: distance between substructure and inner face – value is used for calculation only*

Fig. 3.1: Single components of a fastening

In a first step tests to determine the stiffness of the single components were performed. The stiffness of a single component is included as rotational or longitudinal spring in the model of a fastening presented in Fig. 3.1. If the stiffness of all single components is known, the stiffness of the fastening can be calculated. In addition full-scale tests on fastenings were performed to verify the mechanical model and the stiffness determined for the single components.

The tests on the stiffness of the single components as well as the full-scale tests on fastenings are documented in D3.2 – part 2 [1].

4 Investigations on single components

4.1 Bending stiffness of screw fastener

Bending of the fastener takes place in the unthreaded shank as well as in the threaded part of the fastener, whereat for usual fastenings the unthreaded shank is the longer and therefore decisive part. Therefore for calculation of the bending stiffness also for the threaded part of the fastener the diameter of the unthreaded shank is used. This approach was verified by the bending tests which were executed to determine the stiffness of the clamping into the substructure.

The elastic module is assumed to be E = 200.000 N/mm^2. This corresponds to a stainless steel (e.g. 1.4301), which is a common material for this kind of screw fasteners. In the full-scale tests on fastenings no plastic deflection of the fastener occurred. So only the elastic bending stiffness EI of the fastener is used. EI can be calculated by the following formula.

$$EI = 200.000 N / mm^2 \cdot \frac{\pi \cdot d_S^4}{64} \tag{4.1}$$

with

d_S = diameter of unthreaded shank

4.2 Clamping in the substructure

4.2.1 Bending tests

To determine the stiffness of the clamping of the fastener in the substructure bending tests are performed. The test set-up for the bending tests is given in Fig. 4.1 and Fig. 4.2.

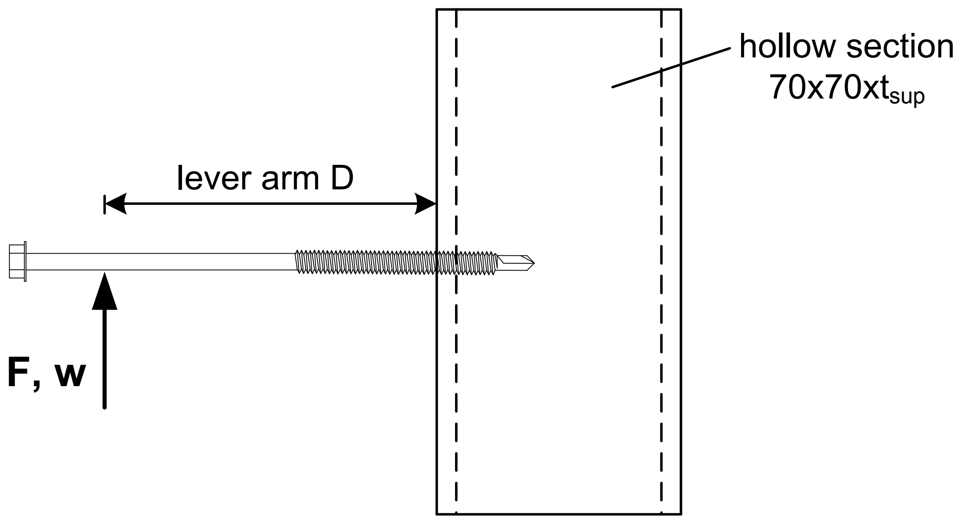


Fig. 4.1: Test set-up of bending tests

Fig. 4.2: Test set-up of bending tests

The screw fastener is mounted into a hollow section and loaded in the manner of a cantilever beam. At the point of load application the fastener can freely rotate. The load is increased until the non-linear part of the load-displacement-relationship is achieved. At the end of the test the fastener is unloaded to zero.

During the tests the wall thickness of the hollow section, the nominal diameter of the fastener and the lever arm D are varied. Tab. 4.1 shows a compilation of the performed bending tests.

The test results of the bending tests are documented in detail in D3.2 – part 2 [1].

No.	thickness of sub-structure [mm]	fastener	pre-drilling diameter [mm]	lever arm D [mm]
2,0-5,5-40	2,0	JT3-6-5,5x170	-	40
2,0-5,5-90				90
2,0-5,5-125				125
3,0-6,3-40	3,0	JZ3-6,3x175	5,3	40
3,0-6,3-90				90
3,0-6,3-125				125
4,0-8,0-40	4,0	JZ3-8,0x150	6,8	40
4,0-8,0-80				80
4,0-8,0-110				100
5,0-5,5-40	5,0	JT3-12-5,5x178	-	40
5,0-5,5-90				90
5,0-5,5-120				120
6,0-6,3-40	6,0	JZ3-6,3x175	5,5	40
6,0-6,3-80				80
6,0-6,3-120				120
8,0-8,0-40	8,0	JZ3-8,0x150	7,2	40
8,0-8,0-80				80
8,0-8,0-110				110

Tab. 4.1: Compilation of bending tests

4.2.2 Evaluation of bending tests

In the full-scale tests on fastenings the inclinations of the fastener was only very small. A plastic deflection and inclination of the fastener occurs only after very large extensions. For serviceability loads there are only elastic deflections and inclinations. Because of that only the linear part of the load-deflection curve is taken into account for evaluation of the bending tests.

For all bending tests the stiffness k of the linear part of the load-deflection curve is determined as shown in Fig. 4.3.

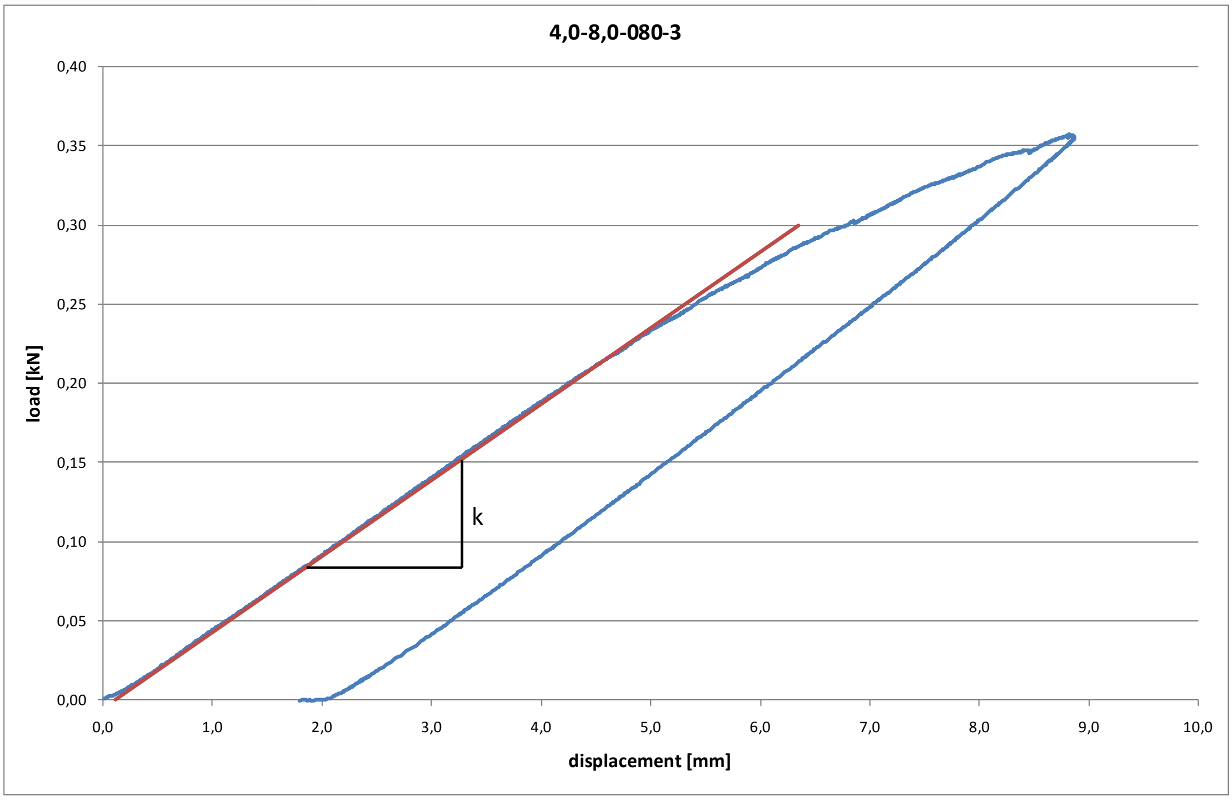


Fig. 4.3: **Example of determination of stiffness k**

The displacement w at point of load introduction consists of two parts - bending of the fastener and rotation of the fastener at the point of clamping in the substructure. The effect of clamping in the substructure can be considered by a rotational spring with the stiffness C (Fig. 4.4). The displacement w at the point of load application is calculate with

$$w = F \cdot \left[\frac{L^3}{3 \cdot EI} + \frac{L^2}{C} \right] = \frac{F}{k} \qquad (4.2)$$

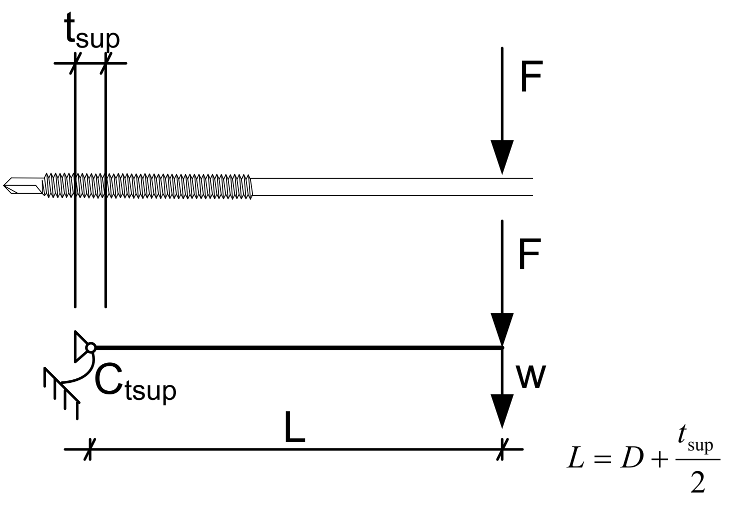


Fig. 4.4: **Mechanical model for evaluation of bending tests**

Based on the stiffness k determined in the tests the stiffness C of the rotational spring is re-calculated.

$$C = \frac{L^2}{\frac{1}{k} - \frac{L^3}{3 \cdot EI}} \tag{4.3}$$

In Tab. 4.2 and Tab. 4.3 the stiffness k determined in the tests as well as the calculated stiffness C of the rotational spring is given. For evaluation of the tests the measured thickness of the substructure t_{sup} is used.

No.	t_{sup} [mm]	D [mm]	L [mm]	d_S [mm]	EI [N/mm^2]	k [N/mm]	C [Nmm]
2,0-5,5-40-1	1,81	40	40,91	4,53	4134212	43,90	96939
2,0-5,5-40-2	1,81	40	40,91	4,53	4134212	43,90	96939
2,0-5,5-40-3	1,81	42	42,91	4,53	4134212	36,12	86354
2,0-5,5-90-1	1,81	90	90,91	4,53	4134212	6,32	84618
2,0-5,5-90-2	1,81	90	90,91	4,53	4134212	7,44	111914
2,0-5,5-90-3	1,81	90	90,91	4,53	4134212	7,00	100424
3,0-6,3-40-1	2,75	40	41,38	5,26	7515240	100,00	249605
3,0-6,3-40-2	2,75	40	41,38	5,26	7515240	88,61	210207
3,0-6,3-40-3	2,75	40	41,38	5,26	7515240	73,53	163687
3,0-6,3-90-1	2,75	90	91,38	5,26	7515240	13,33	202755
3,0-6,3-90-2	2,75	90	91,38	5,26	7515240	12,63	184161
3,0-6,3-90-3	2,75	90	91,38	5,26	7515240	12,00	168694
3,0-6,3-125-1	2,75	125	126,38	5,26	7515240	5,46	170571
3,0-6,3-125-3	2,75	125	126,38	5,26	7515240	5,56	176791
4,0-8,0-40-1	4,12	40	42,06	6,81	21114867	202,90	471253
4,0-8,0-80-1	4,12	80	82,06	6,81	21114867	42,25	450567
4,0-8,0-80-2	4,12	80	82,06	6,81	21114867	47,06	537586
4,0-8,0-80-3	4,12	80	82,06	6,81	21114867	48,15	559055
4,0-8,0-110-1	4,12	110	112,06	6,81	21114867	20,62	477800
4,0-8,0-110-2	4,12	110	112,06	6,81	21114867	20,00	451947
4,0-8,0-110-3	4,12	100	102,06	6,81	21114867	24,81	442796
5,0-5,5-40-3	4,88	40	42,44	4,52	4097827	64,52	194068
5,0-5,5-90-1	4,88	90	92,44	4,52	4097827	7,34	118707
5,0-5,5-90-2	4,88	90	92,44	4,52	4097827	8,89	177171
5,0-5,5-90-3	4,88	90	92,44	4,52	4097827	8,51	160460

Tab. 4.2: Evaluation of bending tests

No.	t_{sup} [mm]	D [mm]	L [mm]	d_S [mm]	EI [N/mm^2]	k [N/mm]	C [Nmm]
5,0-5,5-120-1	4,88	120	122,44	4,52	4097827	3,88	138273
5,0-5,5-120-2	4,88	120	122,44	4,52	4097827	4,00	148891
5,0-5,5-120-3	4,88	120	122,44	4,52	4097827	3,79	130885
6,0-6,3-40-1	5,70	40	42,85	5,26	7515240	111,11	333211
6,0-6,3-40-3	5,70	40	42,85	5,26	7515240	114,81	351725
6,0-6,3-80-1	5,70	80	82,85	5,26	7515240	21,56	324419
6,0-6,3-80-2	5,70	80	82,85	5,26	7515240	20,22	283267
6,0-6,3-80-3	5,70	80	82,85	5,26	7515240	22,22	347014
6,0-6,3-120-1	5,70	120	122,85	5,26	7515240	7,04	252336
6,0-6,3-120-2	5,70	121	123,85	5,26	7515240	6,85	248503
6,0-6,3-120-3	5,70	120	122,85	5,26	7515240	7,41	286286
8,0-8,0-40-2	7,80	41	44,90	6,81	21114867	235,29	714623
8,0-8,0-80-1	7,80	80	83,90	6,81	21114867	50,00	659315
8,0-8,0-80-2	7,80	80	83,90	6,81	21114867	51,25	690880
8,0-8,0-110-1	7,80	112	115,90	6,81	21114867	21,43	608208
8,0-8,0-110-3	7,80	110	113,90	6,81	21114867	22,22	598468

Tab. 4.3: Evaluation of bending tests - continuation

The stiffness C of the rotational spring depends on the thickness t_{sup} and the elastic modulus of the substructure and on the minor diameter d_1 of the fastener.

In Fig. 4.5 the stiffness is opposed to the thickness of the substructure t_{sup}. The stiffness C depends approximately linearly on the square root of the thickness. Values extrapolated to thicknesses, which were not tested, are also given in the diagram. For the extrapolation curves both values obtained in the tests were extrapolated. The mean value of both extrapolated curves is used for the following evaluations.

In Fig. 4.6 the stiffness C is opposed to the minor diameter d_1 of the fasteners. The stiffness C depends approximately linearly with the power of 2,5 on the minor diameter. In Fig. 4.6 also extrapolated values are given.

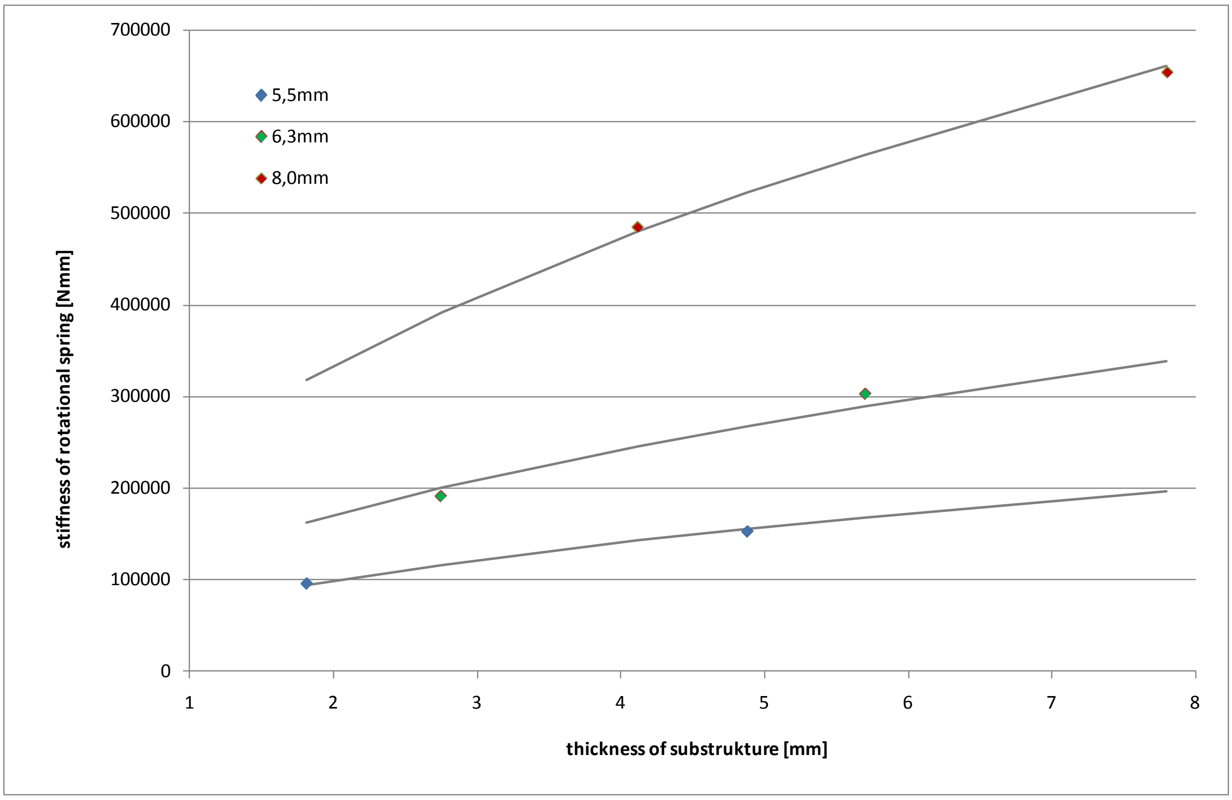


Fig. 4.5: **Stiffness of clamping in the substructure**

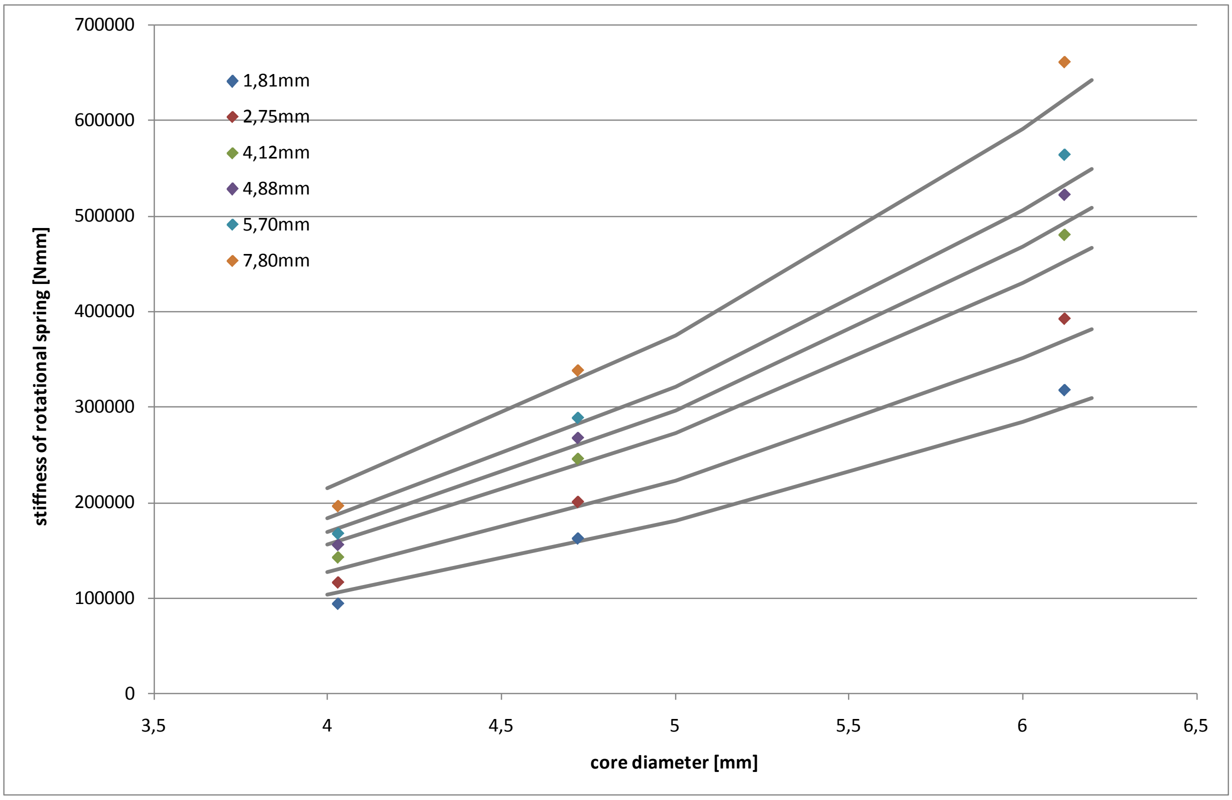


Fig. 4.6: **Stiffness of clamping in the substructure**

So the stiffness of the clamping in the substructure can be calculated by the following formula.

$$C = A \cdot t_{\text{sup}}^{0,5} \cdot d_1^{2,5} \quad (4.4)$$

with

t_{sup} thickness of substructure

d_1 minor diameter of thread

A constant factor [N/mm²] (determined below)

In Tab. 4.4 the mean values of the stiffness of the rotational springs are summarized and the constant factor A is calculated according to (4.4). For the constant factor the mean value A = 2400 N/mm² ensues.

t_{sup} [mm]	d_1 [mm]	C (mean values) [Nmm]	A [N/mm²]
1,81	4,02	96198	2207
2,75	4,72	190809	2377
4,12	6,12	484429	2576
4,88	4,04	152636	2106
5,70	4,72	303345	2625
7,80	6,12	654299	2528
mean value			2403

Tab. 4.4: Mean values of stiffness C

So the stiffness C of the rotational spring representing the clamping of the fastener in the substructure can be determined by the following formula.

$$C = 2400 N/mm^2 \cdot \sqrt{t_{\text{sup}} \cdot d_1^5} \quad (4.5)$$

For most fasteners the minor diameter d_1 can be replaced by

$$d_1 = 0,9 \cdot d_S \quad (4.6)$$

For determination of the stiffness C a constant value of the bending stiffness EI of the fastener was assumed. This stiffness was calculated with the diameter d_S of the unthreaded shank. To use the minor diameter d_1 to calculate the bending stiffness of the threaded part would result in a change in the stiffness C of about 5 %.

In Fig. 4.7 the stiffness C according to the above formula (4.5) is compared to the stiffness determined in the bending tests.

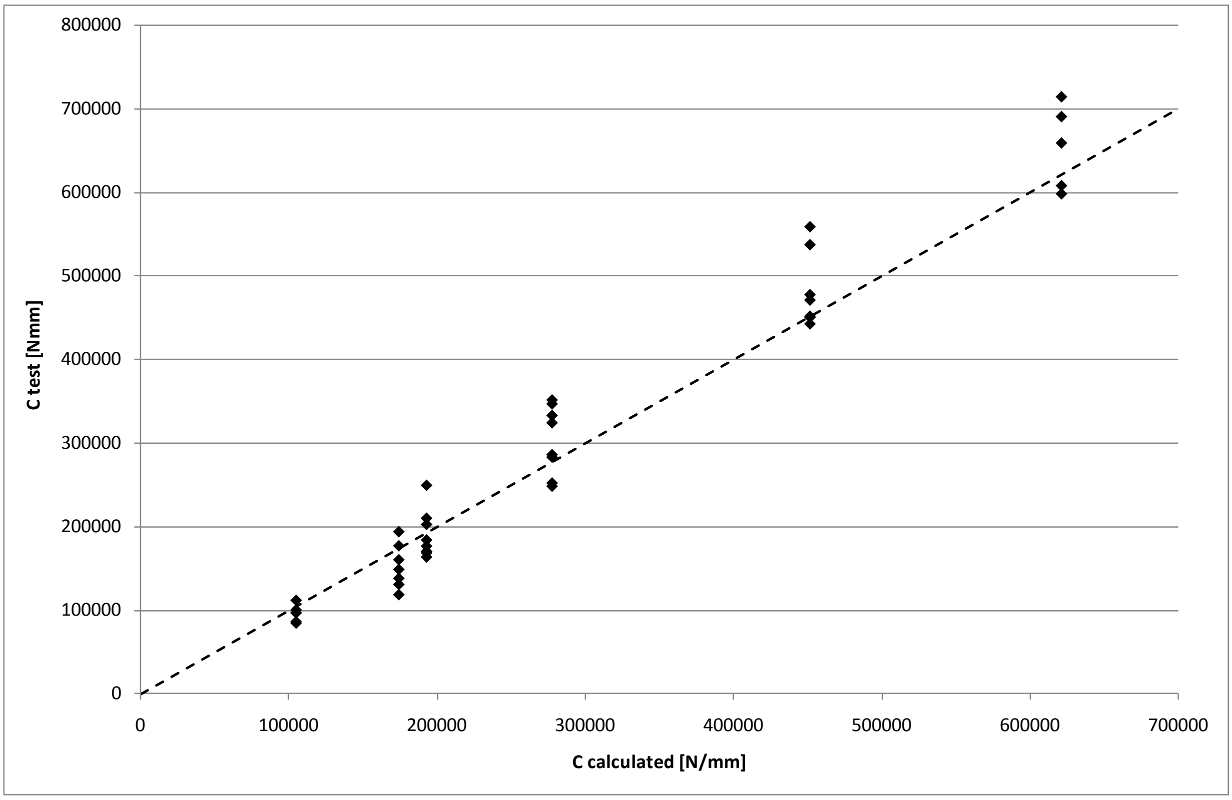


Fig. 4.7: Comparison between tests and calculation

4.3 Hole elongation of face sheets

4.3.1 Hole elongation tests

The test set-up for the hole elongation tests is given in Fig. 4.8 and Fig. 4.9.

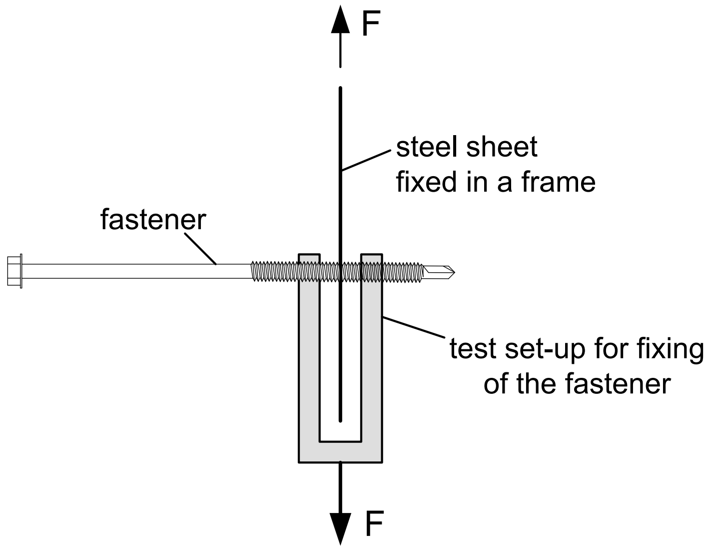


Fig. 4.8: Test set-up of hole elongation tests

Fig. 4.9: Test set-up of hole elongation tests

The fastener is set into the steel sheet. The steel sheet is fixed in a frame and the fastener is also fixed in the test set-up. The specimen is loaded stepwise with an increase of displacement of approximately 0,5 mm in each load step, until a displacement of approximately 3,0 mm is achieved. After each load step the specimen is unloaded to zero.

During the tests the thickness of the steel sheet and the nominal diameter of the fastener are varied. Tab. 4.5 shows a compilation of the performed hole elongation tests.

The results of the hole elongation tests are documented in detail in D3.2 – part 2 [1].

No.	thickness of steel sheet [mm]	fastener	pre-drilling diameter [mm]
0,40-5,5-1	0,40	JT3-6-5,5x170	-
0,40-6,3-1		JZ3-6,3x175	5,0
0,40-8,0-1		JZ3-8,0x150	6,8
0,50-5,5-1	0,50	JT3-6-5,5x170	-
0,50-6,3-1		JZ3-6,3x175	5,0
0,50-8,0-1		JZ3-8,0x150	6,8
0,75-5,5-1	0,75	JT3-6-5,5x170	-
0,75-6,3-1		JZ3-6,3x175	5,0
0,75-8,0-1		JZ3-8,0x150	6,8
1,00-5,5-1	1,00	JT3-6-5,5x170	-
1,00-6,3-1		JZ3-6,3x175	5,0
1,00-8,0-1		JZ3-8,0x150	6,8

Tab. 4.5: Compilation of hole elongation tests

4.3.2 Evaluation of hole elongation tests

Load bearing capacity of elongated holes

The load bearing capacity of an elongated hole depends on the thickness and the tensile strength of the sheet and on the diameter of the fastener or the diameter of the hole. According to EN 1993-1-3 [5] for steel sheets with t < 1,0 mm the load bearing capacity of a fastening depends linearly on the square root of the diameter of the fastener, linearly on the tensile strength of the steel sheet and linearly on the thickness of the steel sheet in the power of 1,5. In the following the load bearing capacity F_F of the elongated hole of a single steel sheet is determined. Following [5] it is assumed that the load bearing capacity F_F can be calculated with

$$F_F = \alpha_F \cdot f_{u,F} \cdot d_1^{0,5} \cdot t_F^{1,5} \qquad (4.7)$$

with

t_F thickness of face sheet

$f_{u,F}$ tensile strength of face sheet

α_F constant factor [-] (determined below)

The above formula is also verified by the performed hole elongation tests. In Fig. 4.10 the ultimate load F_F determined in the tests is opposed to the thickness of the steel sheet. The ultimate loads are adjusted to the tensile strength f_u = 360 N/mm^2.

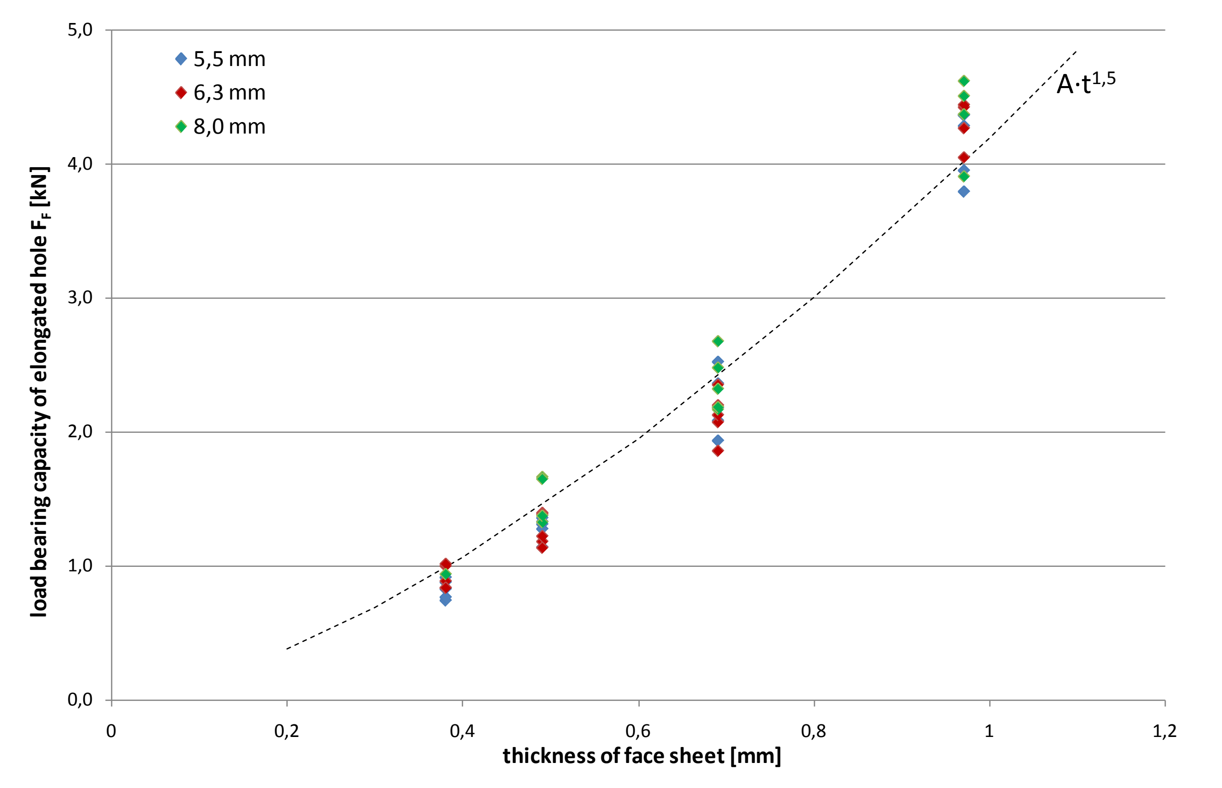


Fig. 4.10: Load bearing capacity of elongated hole

The load bearing capacity of the elongated hole also depends on the diameter of the fastener or on the diameter of the hole. In fastenings of sandwich panels to a substructure the threaded part of the fastener is placed at the internal face of the panel. At the external face the unthreaded shank or an additional support thread is placed. For the load bearing behavior of the fastening the internal face of the panel is decisive (see section 5.2). Therefore for the evaluation of the tests on elongated holes the minor diameter of the thread is used. Furthermore the minor diameter corresponds approximately to the diameter of the hole.

For determination of α_F the core thickness and the tensile strength of the steel sheets and the minor diameter of the thread measured in the tests is used.

The ultimate load F_F determined in the tests as well as the re-calculated factors α_F are summarized in Tab. 4.6 and Tab. 4.7.

t_F [mm]	$f_{u,F}$ [N/mm²]	nominal diameter [mm]	d_1 [mm]	F_F [kN]	α_F [-]
0,38	390	5,5	4,02	0,80	4,36
0,38	390	5,5	4,02	0,89	4,86
0,38	390	5,5	4,02	0,82	4,50
0,38	390	5,5	4,02	0,99	5,38
0,38	390	5,5	4,02	0,95	5,16
0,38	390	6,3	4,72	0,96	4,85
0,38	390	6,3	4,72	1,09	5,47
0,38	390	6,3	4,72	0,91	4,57
0,38	390	6,3	4,72	0,91	4,58
0,38	390	6,3	4,72	1,10	5,55
0,38	390	8,0	6,12	1,02	4,50
0,49	405	5,5	4,02	1,28	4,59
0,49	405	5,5	4,02	1,52	5,47
0,49	405	5,5	4,02	1,47	5,28
0,49	405	5,5	4,02	1,43	5,14
0,49	405	5,5	4,02	1,49	5,36
0,49	405	6,3	4,72	1,57	5,21
0,49	405	6,3	4,72	1,56	5,17
0,49	405	6,3	4,72	1,33	4,41
0,49	405	6,3	4,72	1,38	4,56
0,49	405	6,3	4,72	1,28	4,24
0,49	405	8,0	6,12	1,49	4,34
0,49	405	8,0	6,12	1,87	5,45
0,49	405	8,0	6,12	1,55	4,50
0,49	405	8,0	6,12	1,86	5,40
0,69	387	5,5	4,02	2,34	5,26
0,69	387	5,5	4,02	2,53	5,70
0,69	387	5,5	4,02	2,71	6,09
0,69	387	5,5	4,02	2,08	4,67
0,69	387	5,5	4,02	2,24	5,03
0,69	387	6,3	4,72	2,00	4,15
0,69	387	6,3	4,72	2,53	5,25
0,69	387	6,3	4,72	2,23	4,63
0,69	387	6,3	4,72	2,36	4,91

Tab. 4.6: Determination of α_F

t_F [mm]	$f_{u,F}$ [N/mm²]	nominal diameter [mm]	d_1 [mm]	F_F [kN]	α_F [-]
0,69	387	6,3	4,72	2,29	4,75
0,69	387	8,0	6,12	2,67	4,86
0,69	387	8,0	6,12	2,50	4,55
0,69	387	8,0	6,12	2,33	4,25
0,69	387	8,0	6,12	2,35	4,28
0,69	387	8,0	6,12	2,88	5,24
0,97	394	5,5	4,02	4,78	6,33
0,97	394	5,5	4,02	4,77	6,33
0,97	394	5,5	4,02	4,69	6,21
0,97	394	5,5	4,02	4,15	5,50
0,97	394	5,5	4,02	4,32	5,73
0,97	394	6,3	4,72	4,84	5,92
0,97	394	6,3	4,72	4,43	5,42
0,97	394	6,3	4,72	4,86	5,94
0,97	394	6,3	4,72	4,67	5,71
0,97	394	8,0	6,12	4,78	5,14
0,97	394	8,0	6,12	4,28	4,59
0,97	394	8,0	6,12	4,93	5,30
0,97	394	8,0	6,12	5,06	5,43
mean value					5,10

Tab. 4.7: Determination of α_F - continuation

Regarding all hole elongation tests for the factor α_F a mean value of 5,1 and a characteristic value of 4,2 (5%-quantile) ensue. Therefore the mean value $F_{F,mean}$ and the characteristic value $F_{F,Rk}$ of the load bearing capacity of an elongated hole can be calculated by the following formulae.

Mean value:

$$F_{F,mean} = 5{,}1 \cdot f_{u,F} \cdot \sqrt{t_F^3 \cdot d_1} \qquad (4.8)$$

Characteristic value:

$$F_{F,Rk} = 4{,}2 \cdot f_{u,F} \cdot \sqrt{t_F^3 \cdot d_1} \qquad (4.9)$$

In Fig. 4.11 the above formulae are compared to the ultimate loads determined in the hole elongation tests.

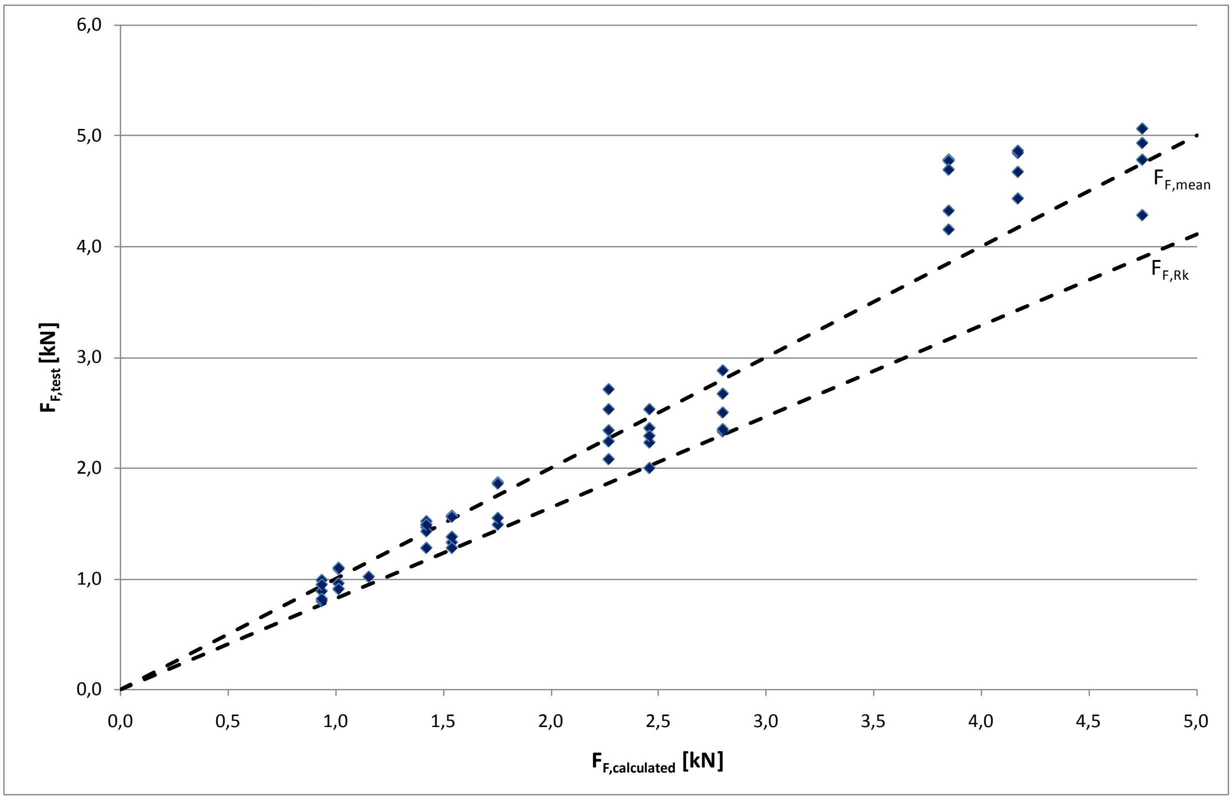


Fig. 4.11: Comparison between test and calculation

<u>Initial stiffness $k_{F,0}$</u>

For the load-displacement curves determined in the hole elongation tests the initial stiffness $k_{F,0}$ is determined. In Fig. 4.12 the initial stiffness is opposed to the core thickness of the steel sheet. Fig. 4.12 shows an approximately linear dependency of the initial stiffness on the thickness of the steel sheet. Obviously the dependency on the diameter of the fastener is negligible.

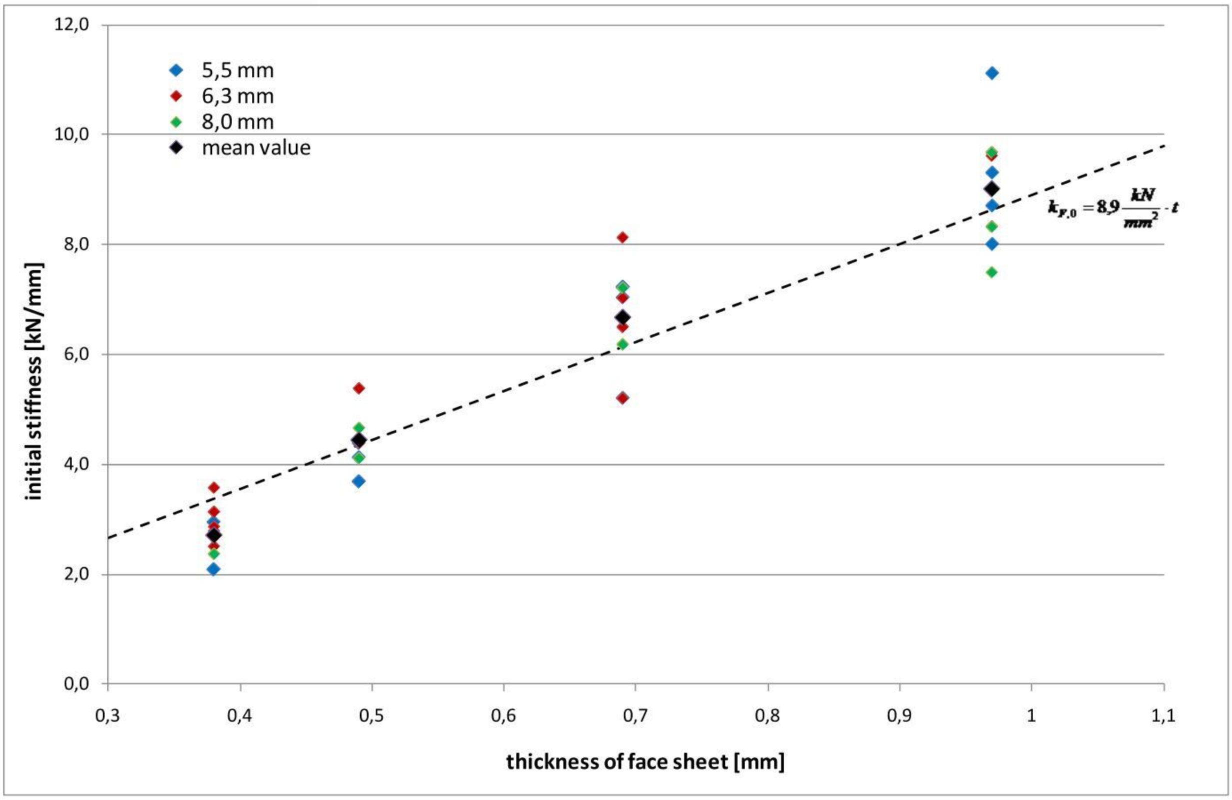


Fig. 4.12: Initial stiffness of elongated hole

Assuming a linear dependency of the initial stiffness on the thickness of the steel sheet, the initial stiffness can be determined according to the following formula.

$$k_{F,0} = A \cdot t_F \tag{4.10}$$

with

A constant factor [N/mm^2]

In Tab. 4.8 and Tab. 4.9 the constant factor A is determined for the performed hole elongation tests. A mean value of A = 8,9 kN/mm^2 ensues.

t [mm]	nominal di-ameter [mm]	$k_{F,0}$ [kN/mm]	A [kN/mm^2]
0,38	5,5	2,94	7,74
0,38	5,5	2,08	5,47
0,38	5,5	2,08	5,47
0,38	6,3	2,78	7,32
0,38	6,3	2,86	7,53
0,38	6,3	3,13	8,24
0,38	6,3	2,50	6,58
0,38	6,3	3,57	9,39
0,38	6,3	3,13	8,24
0,38	8,0	2,38	6,26
0,38	8,0	2,38	6,26
0,49	5,5	4,38	8,94
0,49	5,5	3,68	7,51
0,49	5,5	4,12	8,41
0,49	5,5	3,68	7,51
0,49	6,3	5,38	10,98
0,49	6,3	5,38	10,98
0,49	6,3	4,38	8,94
0,49	8,0	4,67	9,53
0,49	8,0	4,12	8,41
0,49	8,0	4,67	9,53
0,69	5,5	7,03	10,19
0,69	5,5	7,22	10,46
0,69	5,5	5,2	7,54
0,69	5,5	7,22	10,46
0,69	5,5	7,22	10,46
0,69	6,3	8,13	11,78
0,69	6,3	6,5	9,42
0,69	6,3	7,03	10,19
0,69	6,3	6,5	9,42
0,69	6,3	5,2	7,54
0,69	8,0	6,67	9,67
0,69	8,0	6,67	9,67

Tab. 4.8: Evaluation of hole elongation tests

t	nominal diameter	$k_{F,0}$	A
[mm]	[mm]	[kN/mm]	[kN/mm^2]
0,69	8,0	6,19	8,97
0,69	8,0	7,22	10,46
0,69	8,0	6,19	8,97
0,97	5,5	8,70	8,97
0,97	5,5	8,00	8,25
0,97	5,5	11,11	11,45
0,97	5,5	9,30	9,59
0,97	6,3	9,68	9,98
0,97	6,3	9,62	9,92
0,97	6,3	9,68	9,98
0,97	6,3	8,33	8,59
0,97	6,3	8,33	8,59
0,97	8,0	9,68	9,98
0,97	8,0	8,33	8,59
0,97	8,0	7,50	7,73
mean value			8,9

Tab. 4.9: Evaluation of hole elongation tests - continuation

So the initial stiffness of an elongated hole can be determined by the following formula. For comparison in Fig. 4.12 the calculated values of the initial stiffness $k_{F,0}$ are also presented.

$$k_{F,0} = 8900 \frac{N}{mm^2} \cdot t_F \qquad (4.11)$$

Load-displacement relationship of elongated holes

To describe the load-displacement relationship of an elongated hole a Ramberg-Osgood type model can be used. The Ramberg-Osgood type model is also used in [13] to describe the load-displacement relationship of fastenings of sandwich panels with a substructure and fastenings at longitudinal joints. In some of the performed hole elongation tests at first the load as well as the displacement increase. Following the displacement is increasing, whereas the load stays on a nearly constant level or the load increases only very slightly. Finally a further increase of the load occurs, until the maximum load is achieved. The part of the load-displacement curve with increasing displacement and nearly constant load occurs in the hole elongation tests only. In the full-scale tests on fastenings this behaviour cannot be noticed, although the internal face is decisive for the load-displacement relationship of the fastening. Because of this the part with nearly constant load is neglected for the determination of the load-displacement relationship (Fig. 4.13).

The load-displacement relationship is described by the following Ramberg-Osgood type formula.

$$f(F_F) = \frac{F_F}{k_{F,0}} + p_{F,1} \cdot \left(\frac{F_F}{F_{F,1}} \right)^n \qquad (4.12)$$

with

$k_{F,0}$ initial stiffness

$F_{F,1}$ reference load

$p_{F,1}$ residual displacement corresponding to the load $F_{F,1}$

n factor (describes the shape of the curve)

To determine the constant factors $p_{F,1}$ and n in (4.12) in addition to the initial stiffness $k_{F,0}$ two reference points of the load-displacement curve are required. The initial stiffness is calculated according to (4.11). As reference points [$F_{F,Rk}$-f($F_{F,Rk}$)] and [$F_{F,1}$-f($F_{F,1}$)] are chosen. $F_{F,Rk}$ is the characteristic load of a elongated hole according to (4.9). As reference load $F_{F,1} = 0{,}75 \cdot F_{F,Rk}$ is used.
The constant factors of formula (4.12) can be calculated as follows.

$$p_{F,1} = f(F_{F,1}) - \frac{F_{F,1}}{k_{F,0}} \qquad (4.13)$$

$$n = \frac{\ln \dfrac{p_{F,Rk}}{p_{F,1}}}{\ln \dfrac{F_{F,Rk}}{F_{F,1}}} \qquad (4.14)$$

$$p_{F,Rk} = f(F_{F,Rk}) - \frac{F_{F,Rk}}{k_{F,0}} \qquad (4.15)$$

In Tab. 4.10 and Tab. 4.11 the values of f($F_{F,Rk}$) and f($0{,}75 \cdot F_{F,Rk}$) are given. They were determined for the load-displacement curves of the hole elongation tests as shown in Fig. 4.13. In Annex 1 the load displacement curves determined in the tests and the corresponding Ramberg-Osgood type curves are presented.

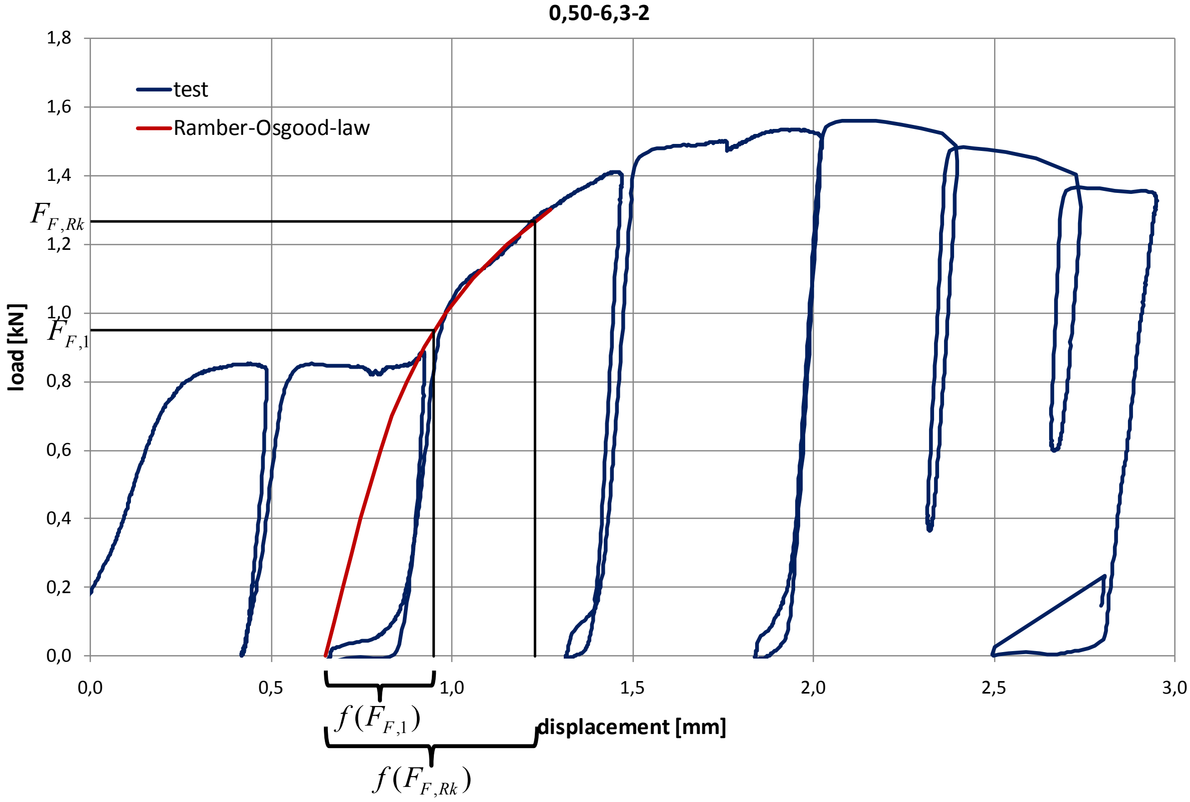


Fig. 4.13: **Example of determination of displacements**

thickness of face sheet [mm]	nominal diameter of fastener [mm]	displacement at characteristic load $f(F_{F,Rk,})$ [mm]	displacement at reference load $f(F_{F,1})$ [mm]
0,38	5,5	0,58	0,25
0,38	5,5	0,47	0,25
0,38	5,5	0,55	0,25
0,38	5,5	0,54	0,30
0,38	5,5	0,51	0,28
0,38	6,3	0,54	0,24
0,38	6,3	0,47	0,25
0,38	6,3	0,67	0,26
0,38	6,3	0,44	0,26
0,38	6,3	0,54	0,25
0,38	8,0	0,80	0,31
0,49	5,5	0,74	0,30
0,49	5,5	0,60	0,32
0,49	5,5	0,61	0,31

Tab. 4.10: **Evaluation of hole elongation tests**

thickness of face sheet [mm]	nominal diameter of fastener [mm]	displacement at characteristic load $f(F_{F,Rk,})$ [mm]	displacement at reference load $f(F_{F,1})$ [mm]
0,49	5,5	0,58	0,34
0,49	5,5	0,67	0,32
0,49	6,3	0,67	0,24
0,49	6,3	0,58	0,30
0,49	6,3	0,68	0,27
0,49	8,0	0,70	0,33
0,49	8,0	0,58	0,28
0,49	8,0	0,76	0,28
0,49	8,0	0,59	0,29
0,69	5,5	0,73	0,35
0,69	5,5	0,91	0,31
0,69	5,5	0,63	0,34
0,69	5,5	0,67	0,31
0,69	6,3	0,54	0,26
0,69	6,3	0,62	0,40
0,69	8,0	0,92	0,32
0,69	8,0	1,15	0,42
0,69	8,0	1,15	0,43
0,97	5,5	0,71	0,42
0,97	5,5	0,71	0,36
0,97	5,5	0,63	0,33
0,97	5,5	0,66	0,36
0,97	5,5	0,69	0,44
0,97	6,3	0,54	0,32
0,97	6,3	0,92	0,50
0,97	6,3	0,51	0,32
0,97	6,3	0,72	0,42
0,97	6,3	0,72	0,38
0,97	8,0	0,70	0,44
0,97	8,0	0,64	0,38
0,97	8,0	0,63	0,40
0,97	8,0	0,60	0,36

Tab. 4.11: Evaluation of hole elongation tests - continuation

Obviously the displacements $f(F_{F,Rk})$ and $f(F_{F,1})$ depend on the thickness of the steel sheet and they are independent of the diameter of the fastener or the influence of the fastener is at least negligible. In Tab. 4.12 the mean values of the displacements are summarised. The displacement $f(F_{F,Rk})$ corresponding to the characteristic load $F_{F,Rk}$ can be calculated approximately by the following formulae.

$$f(F_{F,Rk}) = 0{,}26mm + 0{,}8 \cdot t_F \qquad 0{,}40mm \le t_F \le 0{,}70mm \qquad (4.16)$$

$$f(F_{F,Rk}) = 0{,}82mm \qquad 0{,}70mm \le t_F \le 1{,}00mm \qquad (4.17)$$

In Tab. 4.12 the displacement $f(F_{F,Rk})$ determined by the above formulae is compared to the displacement $f(F_{F,1})$ determined by the tests. The mean value of the quotients of both displacements is

$$\frac{f(F_{F,Rk})}{f(F_{F,1})} = 2{,}2 \qquad (4.18)$$

thickness of face sheet [mm]	$f(F_{F,Rk})$ test [mm]	$f(F_{F,Rk})$ calculated [mm]	$f(F_{F,1})$ test [mm]	$\frac{f(F_{F,Rk})calculated}{f(F_{F,1})test}$ [-]
0,38	0,56	0,56	0,26	2,14
0,49	0,65	0,65	0,30	2,19
0,69	0,81	0,81	0,35	2,33
0,97	0,67	0,82	0,39	2,11
mean value				2,2

Tab. 4.12: Mean values of displacements

So the displacement $f(F_{F,1})$ corresponding to the load $F_{F,1} = 0{,}75 \cdot F_{F,Rk}$ can be calculated as follows

$$f(F_{F,1}) = \frac{0{,}26mm + 0{,}8 \cdot t_F}{2{,}2} = 0{,}118mm + 0{,}364 \cdot t_F \qquad 0{,}40mm \le t_F \le 0{,}70mm \qquad (4.19)$$

$$f(F_{F,1}) = \frac{0{,}82mm}{2{,}2} = 0{,}373mm \qquad 0{,}70mm \le t_F \le 1{,}00mm \qquad (4.20)$$

In Fig. 4.14 the mean values of the displacements determined in the tests are compared to the values calculated by the above formulae.

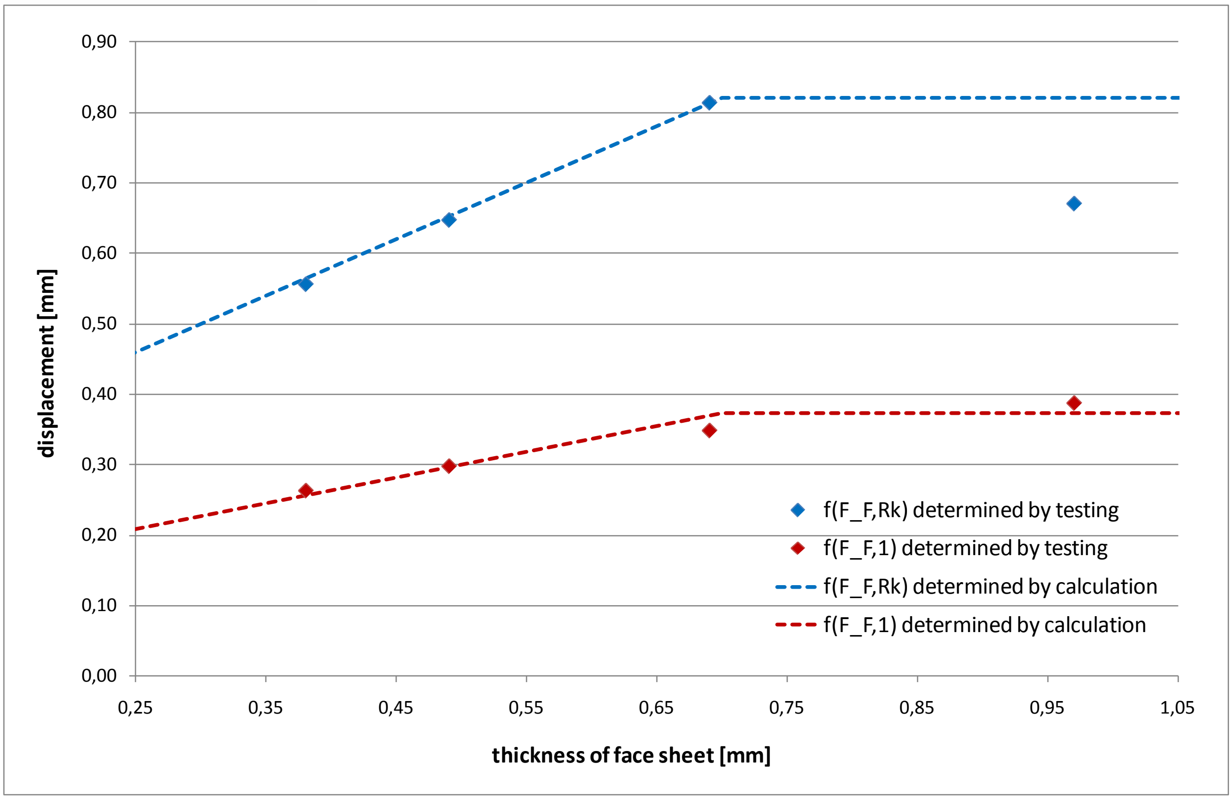


Fig. 4.14: Comparison of displacements determined by calculation and by testing

To determine the stiffness of a fastening the load-displacement relationship of the elongated hole is simplified. Instead of the Ramberg-Osgood type model a bilinear approximation is used. The bilinear curve is defined by the reference points [$F_{F,1}$-f($F_{F,1}$)] and [$F_{F,Rk}$-f($F_{F,Rk}$)] as shown in Fig. 4.15. The stiffness of the first part of the bilinear curve is k_{FI}, the second part has the stiffness k_{FII}.

The stiffness k_{FI} and k_{FII} is calculated as follows.

$$k_{FI} = \frac{F_{F,1}}{f(F_{F,1})} = \frac{0{,}75 \cdot F_{F,Rk}}{\frac{f(F_{F,Rk})}{2{,}2}} \tag{4.21}$$

$$k_{FI} = 1{,}65 \cdot \frac{4{,}2 \cdot f_{u,F} \cdot \sqrt{t_F^3 \cdot d_1}}{0{,}26mm + 0{,}8 \cdot t_F} = 6{,}93 \cdot \frac{f_{u,F} \cdot \sqrt{t_F^3 \cdot d_1}}{0{,}26mm + 0{,}8 \cdot t_F} \qquad 0{,}40mm \le t_F \le 0{,}70mm \tag{4.22}$$

$$k_{FI} = \frac{4{,}2 \cdot f_{u,F} \cdot \sqrt{t_F^3 \cdot d_1}}{0{,}373mm} \qquad 0{,}70mm \le t_F \le 1{,}00mm \tag{4.23}$$

$$k_{FII} = \frac{F_{F,Rk} - F_{F,1}}{f(F_{F,Rk}) - f(F_{F,1})} = \frac{0{,}25 \cdot F_{F,Rk}}{0{,}545 \cdot f(F_{F,Rk})} = 0{,}278 \cdot k_{FI} \tag{4.24}$$

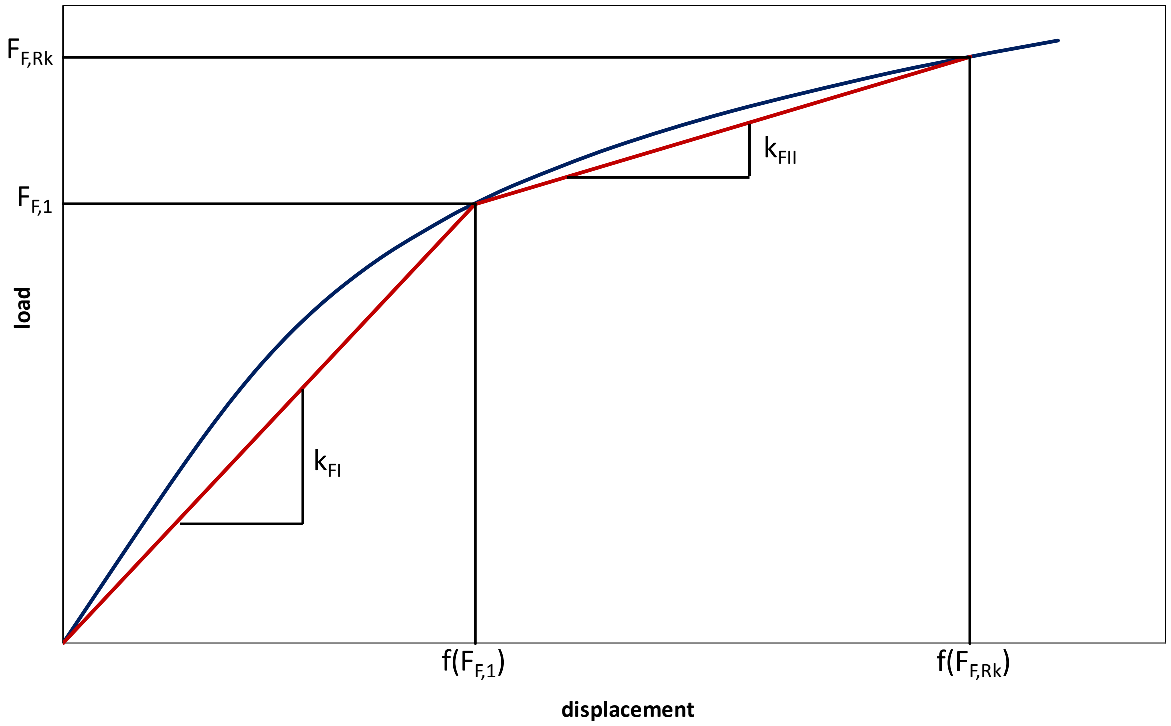


Fig. 4.15: Ramberg-Osgood type model and bilinear approximation

4.4 Clamping of the head of the fastener

4.4.1 Tests on the clamping of the head

For investigating the effect of the clamping of the head at the external face sheet full-scale tests on fastenings of sandwich panels and a substructure are performed. For these tests two kinds of specimens are used. In the first tests series (series a) the fastenings are executed in the usual way. In the second test series (series b) the panels are screwed to the substructure developing a gap between the external face of the panel and the washer of the fastener (Fig. 4.16). In test series b the head of the fastener can freely rotate and so there is not any clamping of the head of the fastener.

Fig. 4.16: Fastenings of test series a and b

A test set up according to the ECCS-recommendations [9], [10] is used. In each test two fastenings are tested. The test set up is given in Fig. 4.17 and Fig. 4.18.

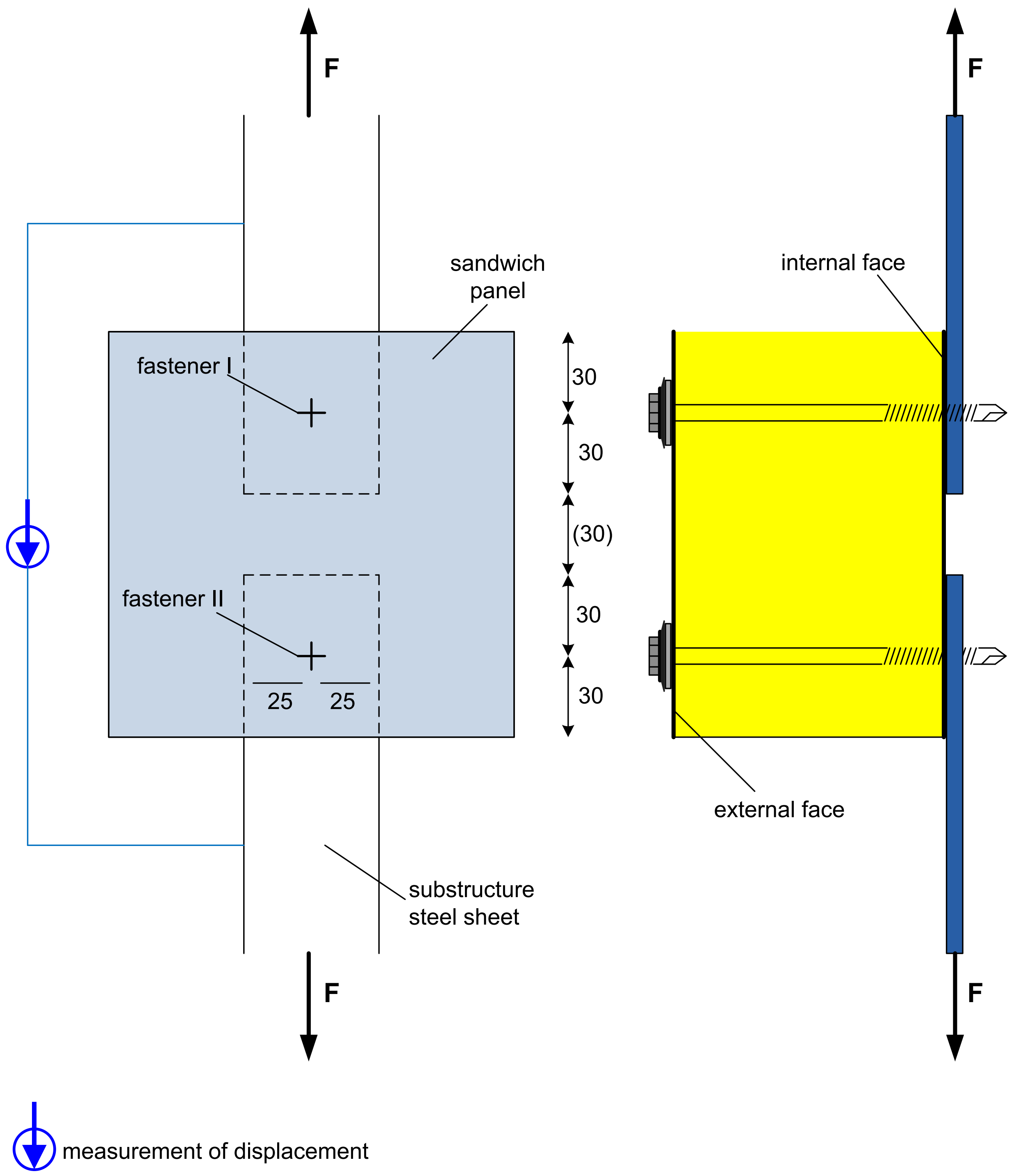


Fig. 4.17: Test set-up of full-scale tests

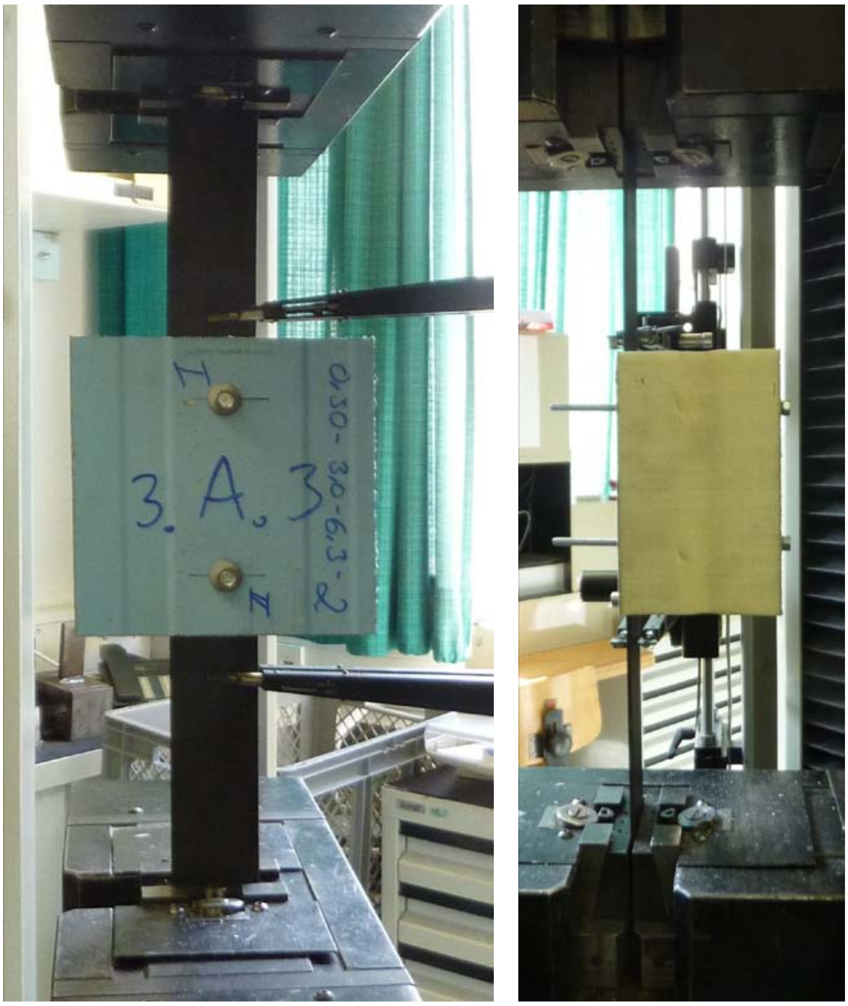


Fig. 4.18: Test set-up of full-scale tests

Tab. 4.13 shows a compilation of the tests on the clamping of the head of the fastener.

No.	fastener	pre-drilling diameter [mm]	type of panel / thickness of faces [mm]	thickness of substructure [mm]	clamping of head
0,60-2,0-5,5-a	JT3-6-5,5x130	-	C / 0,60	2,0	yes
0,60-3,0-6,3-a	JZ3-6,3x150	5,3	C / 0,60	3,0	yes
0,75-6,0-6,3-a	JZ3-6,3x150	5,5	B / 0,75	6,0	yes
0,60-2,0-5,5-b	JT3-6-5,5x130	-	C / 0,60	2,0	no
0,60-3,0-6,3-b	JZ3-6,3x150	5,3	C / 0,60	3,0	no
0,75-6,0-6,3-b	JZ3-6,3x150	5,5	B / 0,75	6,0	no

Tab. 4.13: Compilation of tests on clamping of the head

4.4.2 Results of the tests

In Fig. 4.19 to Fig. 4.21 the load-extension curves of the tests on fastenings with clamping of the head and without clamping of the head are compared.

In the first part of the curve the clamping of the head has not any influence on the load-displacement relationship. In the second part of the curve a difference occurs. For fastenings with clamping of the head there is a further increase of the load, whereas for the fastenings without clamping of the head the load remains approximately on a constant level. During the increase of the load at the first part of the curve the hole in the internal face of the panel is elongated and a slight inclination of the fastener occurs. Because of the inclination in common fastenings without a gap a part of the load is no longer carried by shear forces but by tensile forces. The fastenings with a gap between the washer and the external face sheet cannot carry any tensile forces. Therefore in the tests with common fastenings slightly higher loads are achieved.

The difference between the load-displacement curves for fastenings with clamping of the head and without clamping of the head decreases with increasing thickness of the substructure. For thick substructures the clamping of the fastener in the substructure is stiffer than for thin sub-structures. Therefore the inclination of the fastener and also the tensile forces are smaller.

For determination of the load bearing capacity of fastenings subjected to shear forces it is recommended not to take tensile forces into account. In addition the tensile forces are only activated after relatively large displacements. So neglecting these tensile forces is on the safe side. The stiffness of a fastening has to be determined for serviceability loads [8], [9], [12]. So only the first part of the load-displacement curve is relevant to determine the stiffness of a fastening. In this part the clamping of the head has not any influence on the load-displacement behaviour. Because of that in the following the clamping of the head is neglected for the determination of both, the load bearing capacity and the stiffness of a fastening.

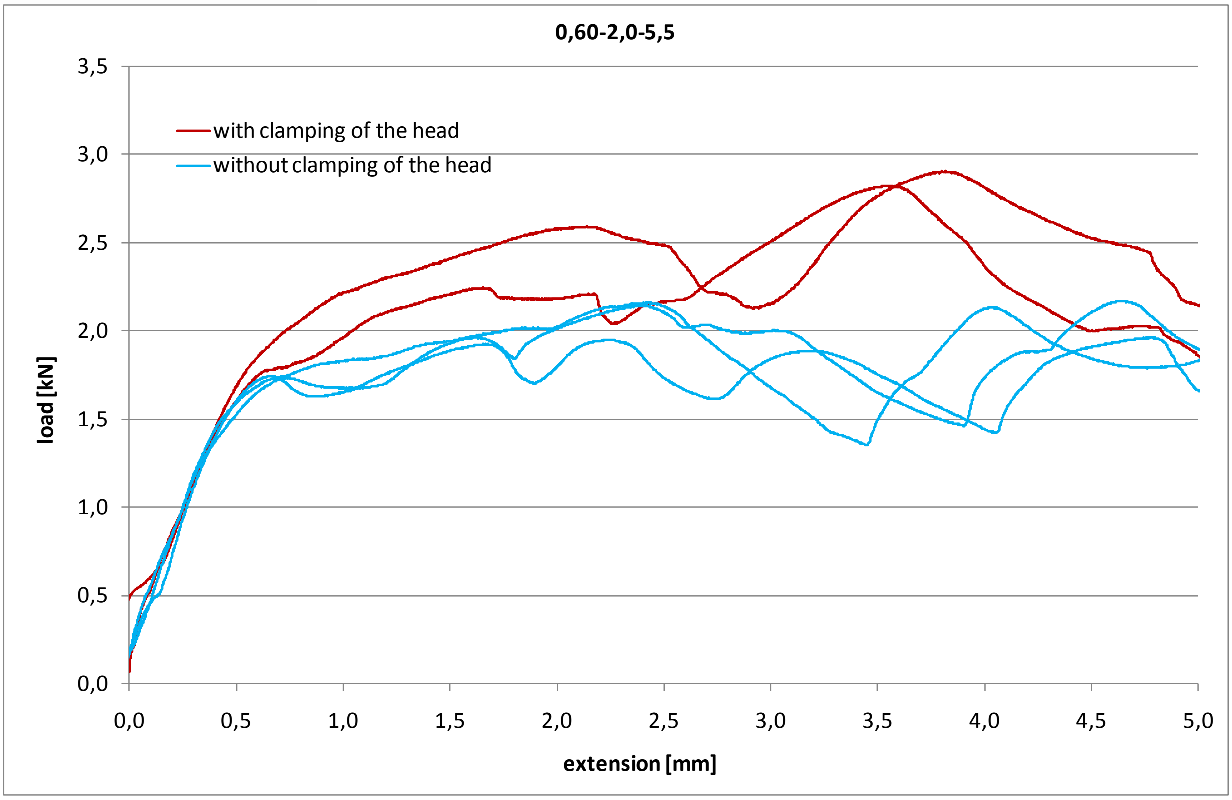


Fig. 4.19: **Influence of clamping of the head (series 060-20-55)**

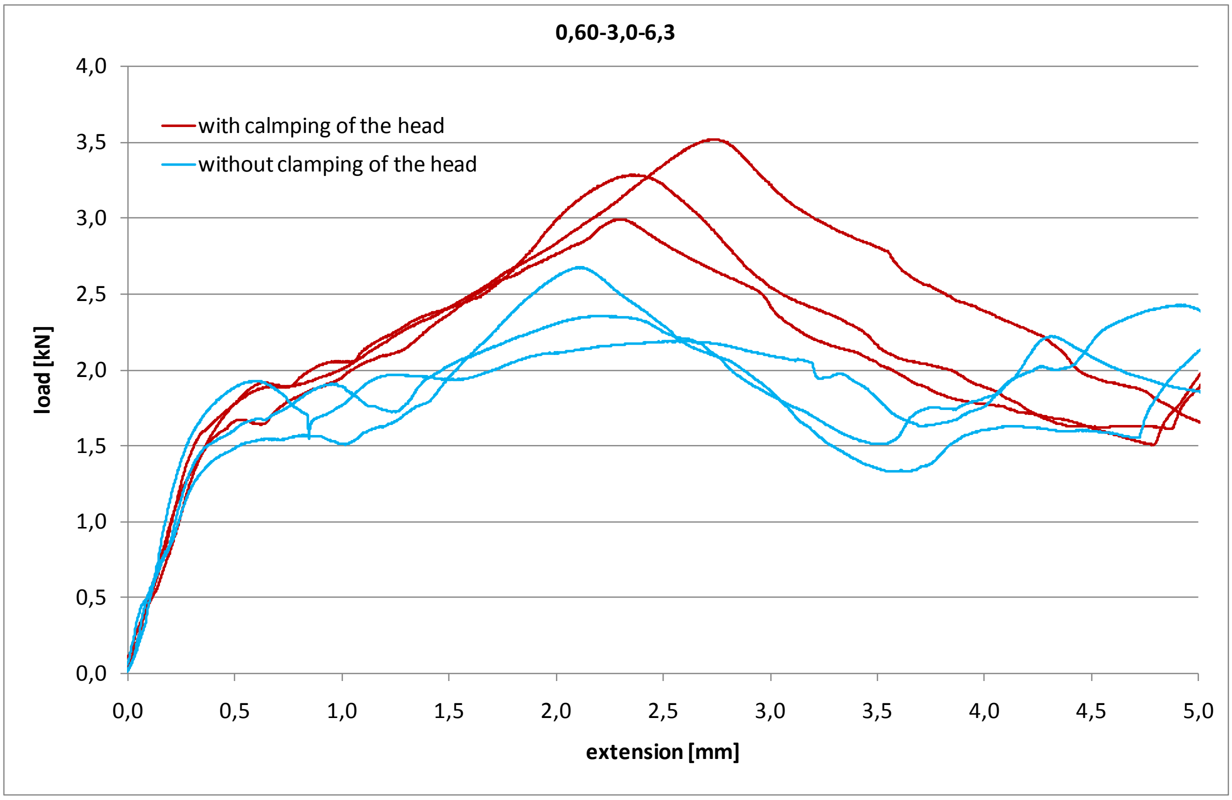


Fig. 4.20: **Influence of clamping of the head (test series 060-30-60)**

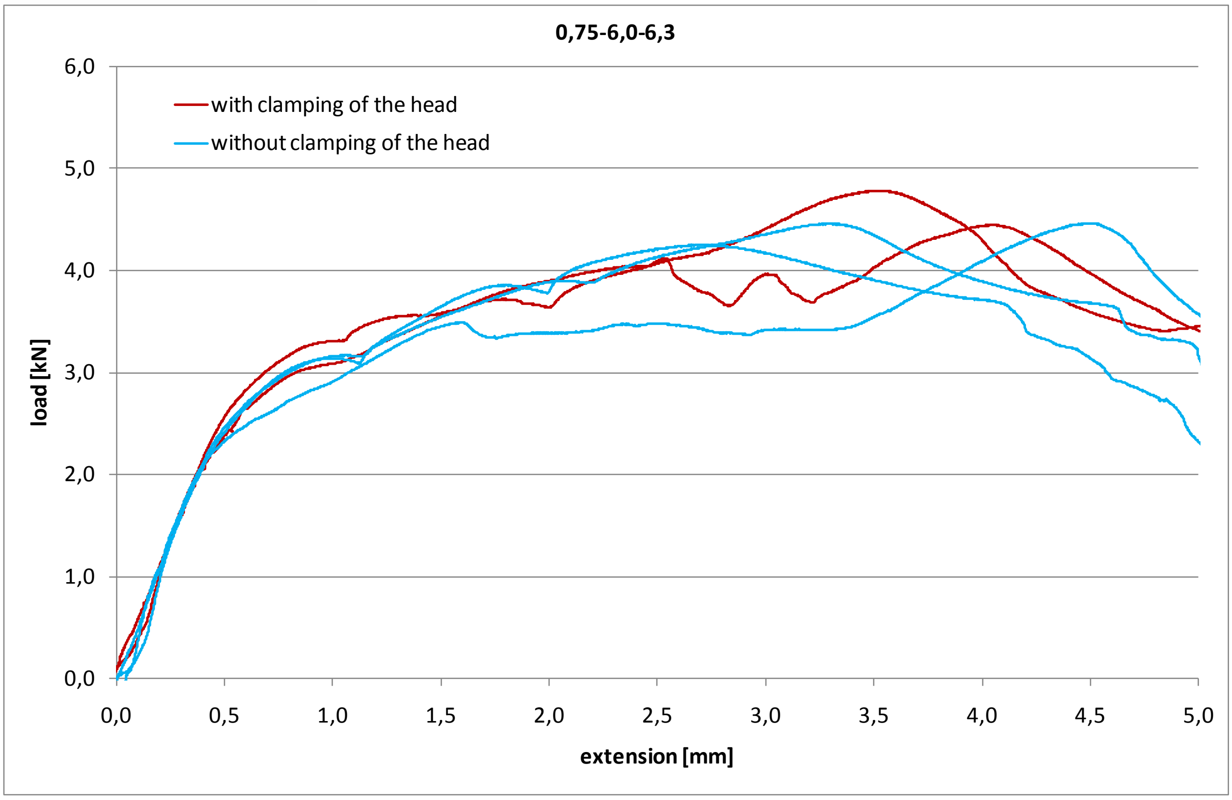


Fig. 4.21: Influence of clamping of the head (test series 075-60-63)

5 Stiffness and load bearing capacity of fastenings

5.1 Mechanical model

To determine the load bearing capacity and the stiffness of a shear loaded fastening of a sandwich panel and a substructure the mechanical model presented in Fig. 5.1 is used. The fastener is clamped in the substructure. The effect of clamping is represented by a rotational spring with the stiffness C. The stiffness C was determined in section 4.2. The face sheets of the panel are represented by longitudinal springs. The load bearing capacity F_F and the stiffness k_F of the longitudinal springs were determined in section 4.3. In the mechanical model the rotational spring representing the clamping in the substructure and the longitudinal spring representing the internal face sheet have the distance t*. The distance t* is assumed to be

$$t^* = \frac{t_{sup}}{2} \qquad (5.1)$$

This assumption was verified by the full-scale tests on fastenings. As presented in section 4.4 the clamping of the head of the fastener is neglected.

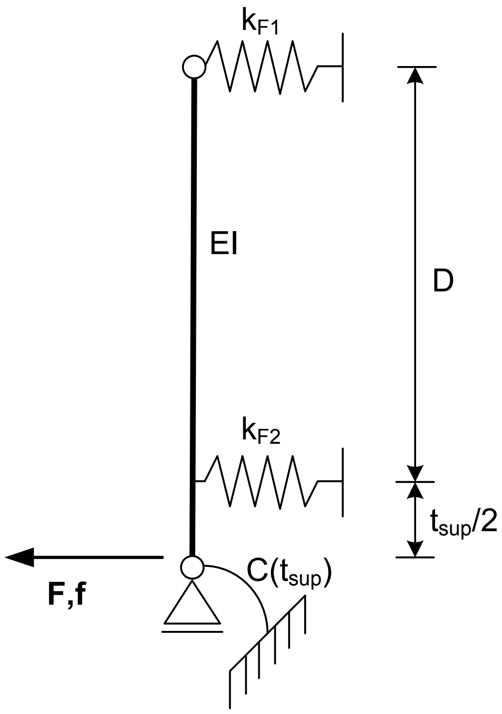


Fig. 5.1: Mechanical model of a fastening

Using the mechanical model presented above the stiffness and the load-bearing capacity of a fastening can be determined. The load-displacement relationship resulting from the hole elongation of a face sheet is described by a bilinear approximation with the stiffness k_{FI} and k_{FII} (section 4.3). For the load bearing capacity F_{Rk} and the stiffness k_v of a fastening the internal face sheet is decisive. Therefore also for the load-displacement relationship of a fastening a bilinear curve ensues (Fig. 5.2).

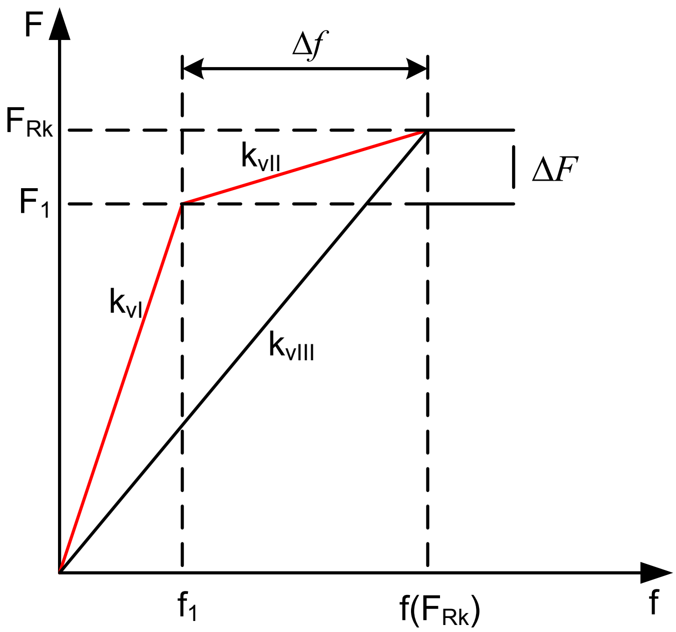


Fig. 5.2: Bilinear load-displacement relationship of a fastening

If the force $F_{F,1}$ is achieved at the internal face sheet, the fastening is loaded with the force F_1. If the load bearing capacity $F_{F,Rk}$ of the internal face sheet is achieved, the fastening is loaded by the load F_{Rk}. The stiffness of the fastening k_{vI} and k_{vII} is

$$k_{vI} = \frac{F_1}{f_1} \tag{5.2}$$

$$k_{vII} = \frac{\Delta F}{\Delta f} = \frac{F_{Rk} - F_1}{f(F_{Rk}) - f_1} \tag{5.3}$$

Instead of a bilinear approximation also a linear approximation with the stiffness k_{vIII} would be possible.

$$k_{vIII} = \frac{F_{Rk}}{f(F_{Rk})} \tag{5.4}$$

5.2 Influence of the external face sheet

To investigate the influence of the stiffness of the external face sheet the stiffness k_{vI} of the fastening is considered. The stiffness k_{vI} is the decisive stiffness for the design of fastenings. First the extreme examples – rigid support and no support – are considered (Fig. 5.3).

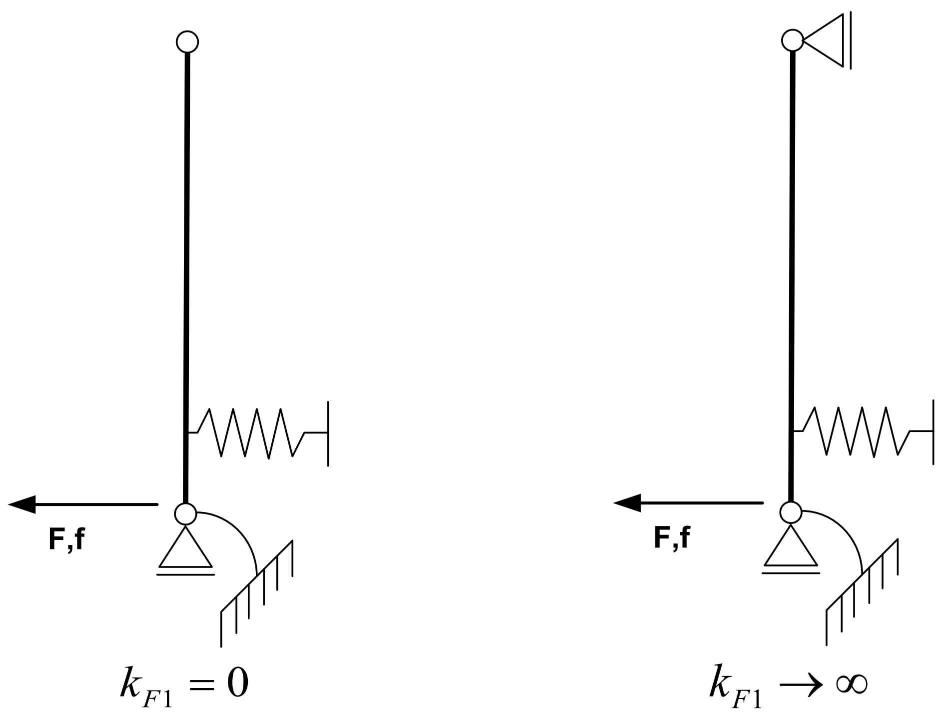


Fig. 5.3: Mechanical models for fastenings with different stiffness of the external face

In Fig. 5.4 for both cases each with a relatively thick (10 mm) and with a relatively thin (1,5 mm) substructure the stiffness k_{vl} is compared. Obviously for thick substructures there is an influence of the external face sheet. In addition in Fig. 5.4 the stiffness of the fastening is given for the cases $k_{F1} = k_{F2}$ and $k_{F1} = 0{,}1 \cdot k_{F2}$. Even if the stiffness of the external face sheet is only 10% of the stiffness of the internal face sheet, the stiffness of the fastening is approximately equal to the stiffness of a fastening with a rigid support. Only very small forces are introduced in the external face. This is confirmed by full-scale tests on fastenings. The forces introduced in the external face sheet are as small as no measurable elongation of the hole occurs.

Therefore for determination of load-bearing capacity and stiffness of a fastening the external face is assumed to be a rigid support. This assumption simplifies the mechanical model. As a further advantage the load bearing capacity and the stiffness of a fastening depend on the characteristics of the internal face sheet only. The characteristics of the external face sheet need not to be taken into account. Furthermore a support thread under the head of the fastener has no influence of the stiffness and the load bearing capacity.

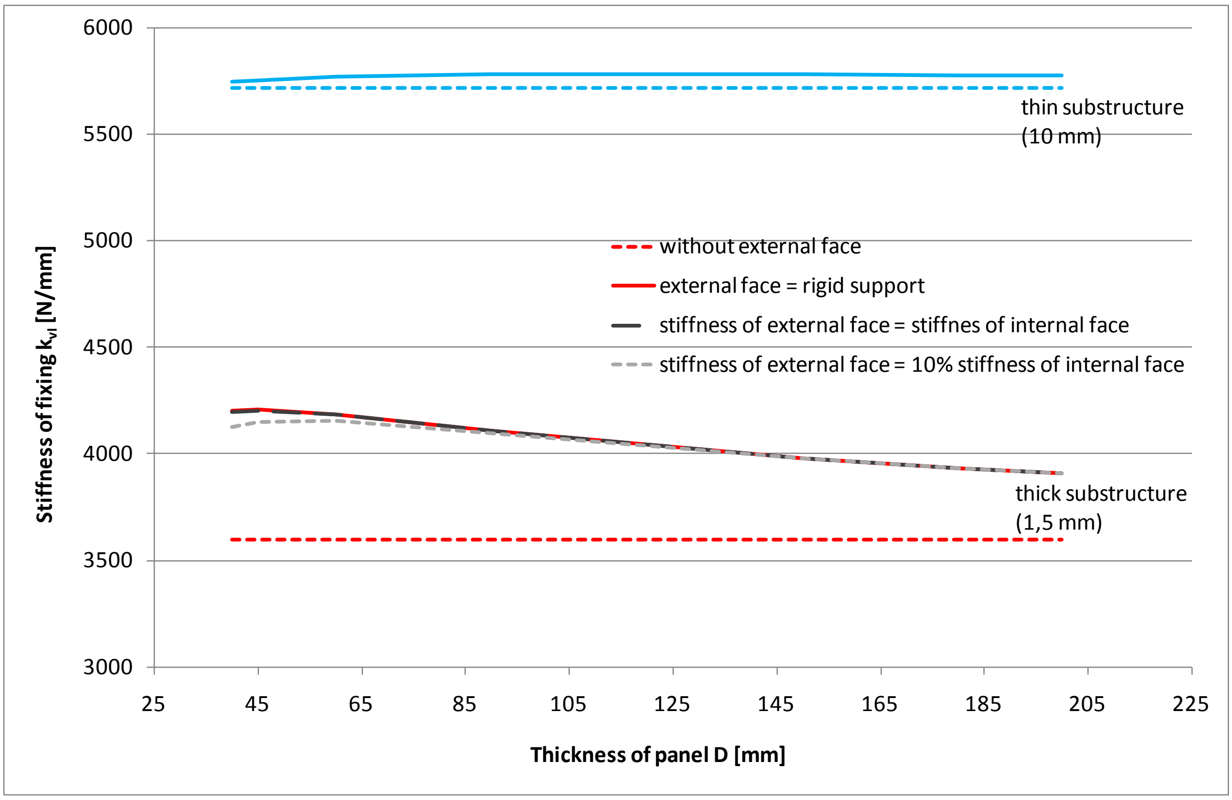


Fig. 5.4: Influence of the external face sheet

In the following the formulae to determine the load-displacement relationship and the stiffness k_v of a fastening are presented. The formulae refer to the mechanical model given in Fig. 5.3.

The external face sheet is assumed to be a rigid support. For calculating the stiffness k_F the characteristics of the internal face have to be used (t_{F2}, $f_{u,F2}$, k_{F2}).

$$x_{Fi} = 1 - \frac{\frac{1}{k_{F2i}} - \frac{D \cdot t_{\sup}}{2 \cdot C} - \frac{D \cdot t_{\sup}^2}{8 \cdot EI}}{\frac{1}{k_{F2i}} + \frac{D^2}{C} + \frac{D^2 \cdot (2 \cdot D + 3 \cdot t_{\sup})}{6 \cdot EI}} \tag{5.5}$$

$$i = I, II$$

$$F_1 = \frac{0{,}75 \cdot F_{F,Rk}}{x_{FI}} \tag{5.6}$$

$$f_1 = F_1 \cdot \left[\frac{x_{FI}}{k_{F2I}} + \frac{t_{\sup}^2 + 2 \cdot (1 - x_{FI}) \cdot D \cdot t_{\sup}}{4 \cdot C} + \frac{3 \cdot (1 - x_{FI}) \cdot D \cdot t_{\sup}^2 + 2 \cdot t_{\sup}^3}{24 \cdot EI} \right] \tag{5.7}$$

$$\Delta F = \frac{0{,}25 \cdot F_{F,Rk}}{x_{FII}} \tag{5.8}$$

$$\Delta f = \Delta F \cdot \left[\frac{x_{FII}}{k_{F2II}} + \frac{t_{\sup}^2 + 2 \cdot (1 - x_{FI}) \cdot D \cdot t_{\sup}}{4 \cdot C} + \frac{3 \cdot (1 - x_{FI}) \cdot D \cdot t_{\sup}^2 + 2 \cdot t_{\sup}^3}{24 \cdot EI} \right] \tag{5.9}$$

$$F_{Rk} = F_1 + \Delta F \tag{5.10}$$

$$f(F_{Rk}) = f_1 + \Delta f \tag{5.11}$$

$$k_{vI} = \frac{F_1}{f_1} = \frac{1}{\frac{x_{FI}}{k_{F2I}} + \frac{t_{\sup}^2 + 2 \cdot (1 - x_{FI}) \cdot D \cdot t_{\sup}}{4 \cdot C} + \frac{3 \cdot (1 - x_{FI}) \cdot D \cdot t_{\sup}^2 + 2 \cdot t_{\sup}^3}{24 \cdot EI}} \tag{5.12}$$

$$k_{vII} = \frac{\Delta F}{\Delta f} = \frac{1}{\frac{x_{FII}}{k_{F2II}} + \frac{t_{\sup}^2 + 2 \cdot (1 - x_{FI}) \cdot D \cdot t_{\sup}}{4 \cdot C} + \frac{3 \cdot (1 - x_{FI}) \cdot D \cdot t_{\sup}^2 + 2 \cdot t_{\sup}^3}{24 \cdot EI}} \tag{5.13}$$

$$k_{vIII} = \frac{F_{Rk}}{f(F_{Rk})} \tag{5.14}$$

5.3 Load bearing capacity of fastenings

The load bearing capacity of a fastening is limited by the load bearing capacity of the elongated hole of the internal face. In Fig. 5.5 the load bearing capacity of the fastening is compared to the load bearing capacity of the internal face sheet. Only for thin sandwich panels with relatively thick face sheets a small difference occurs. For the application range considered in the report at hand the difference between load bearing capacity of fastening and load bearing capacity of internal face sheet is less than 4%. Simplifying the load bearing capacity of an elongated hole of the internal face sheet can be used for the load bearing capacity of the fastening.

$$F_{Rk} \approx F_{F,Rk} = 4{,}2 \cdot \sqrt{t_{F2}^3 \cdot d_1} \cdot f_{u,F2} \tag{5.15}$$

To get the design value of the load bearing capacity the characteristic value has to be divided by the material safety factor γ_{m2}.

$$F_{Rd} = \frac{F_{Rk}}{\gamma_{M2}} \tag{5.16}$$

The material safety factor γ_{M2} is given by national specifications. According to EN 1993-1-3 γ_{M2} = 1,25 is recommended. If the load bearing capacity is determined by testing according to different approvals γ_{M2} = 1,33 has to be used.

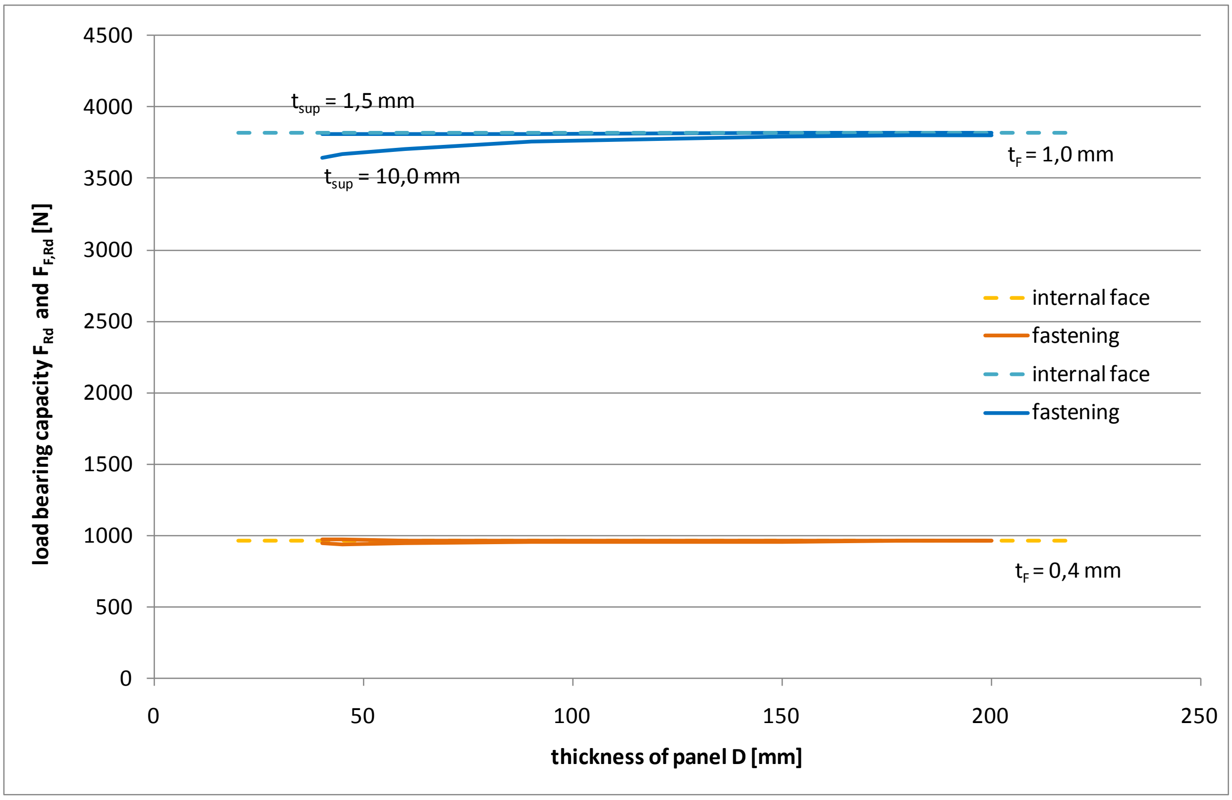


Fig. 5.5: Load bearing capacity of fastenings

5.4 Stiffness of fastenings

For serviceability loads the loading of a fastening does not exceed the force F_1. Therefore for design purposes - e.g. determination of stiffness of a shear diaphragm – the stiffness k_{vl} should be used.

$$k_v = k_{vI} \tag{5.17}$$

5.5 Verification of the design model

5.5.1 Comparison to test results

For verification of the design model some full-scale tests on fastenings were performed. A test set up according to the ECCS-recommendations [9], [10] was used. In each test two fastenings were tested. The test set up is given in section 4.4.1 (tests on clamping of the head).
During the tests the thickness of the substructure and of the face sheets as well as the nominal diameter of the fastener were varied. Tab. 5.1 shows a compilation of the full-scale tests.

No.	fastener	pre-drilling diameter [mm]	thickness of sub-structure [mm]	type of panel / thickness of faces [mm]
0,50-2,0-5,5	JT3-6-5,5x130	-	2,0	A / 0,50
0,50-3,0-6,3	JZ3-6,3x150	5,3	3,0	A / 0,50
0,50-4,0-8,0	JZ3-8,0x150	6,8	4,0	A / 0,50
0,60-2,0-5,5	JT3-6-5,5x130	-	2,0	C / 0,60
0,60-3,0-6,3	JZ3-6,3x150	5,3	3,0	C / 0,60
0,60-4,0-8,0	JZ3-8,0x150	6,8	4,0	C / 0,60
0,60-5,0-5,5	JT3-12-5,5x138	-	5,0	C / 0,60
0,60-6,0-6,3	JZ3-6,3x150	5,5	6,0	C / 0,60
0,60-8,0-8,0	JZ3-8,0x150	7,2	8,0	C / 0,60
0,75-5,0-5,5	JT3-12-5,5x138	-	5,0	B / 0,75
0,75-6,0-6,3	JZ3-6,3x150	5,5	6,0	B / 0,75
0,75-8,0-8,0	JZ3-8,0x150	7,2	8,0	B / 0,75

Tab. 5.1: Compilation of full-scale tests

The load-extension curves determined in the tests are compared to the curves determined by calculation using the formulae given in section 5.4. The following figure shows an exemplary comparison of calculated and tested load-extension curves. The diagrams for the remaining tests are presented in Annex 2.
Especially for the first part of the load-displacement relationship corresponding to the stiffness k_{vl}, which has to be used for design purposes, the curves agree very well.

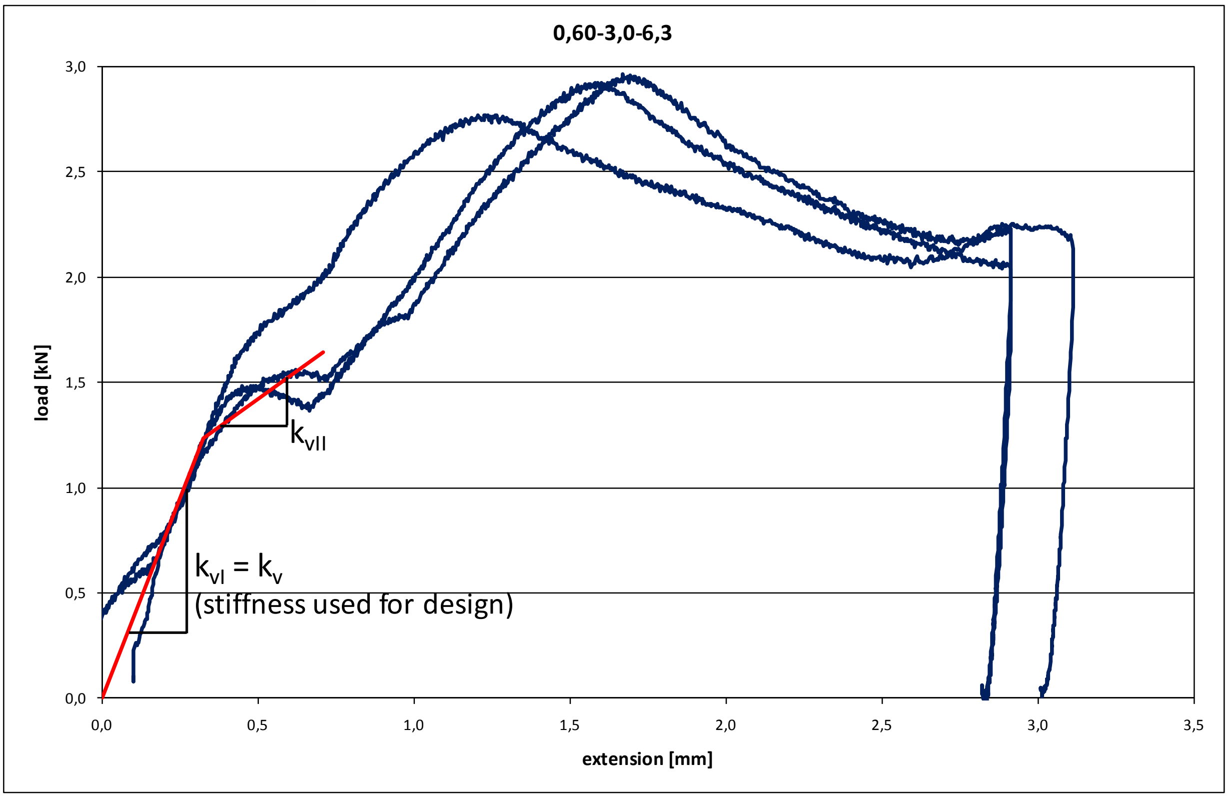


Fig. 5.6: **Comparison of calculated and tested load-extension curve**

To verify the formula for calculation of the load bearing capacity calculated values are compared to the results of the tests on fastenings without clamping of the head (test series b, section 4.4.1). In these fastenings tensile forces cannot occur. Therefore the load bearing behaviour corresponds to the mechanical model. In the following figures the load-extension curves determined in the tests and the calculated mean values of the load-bearing capacity according to (4.8) are shown. Also these values correspond well to the test results.

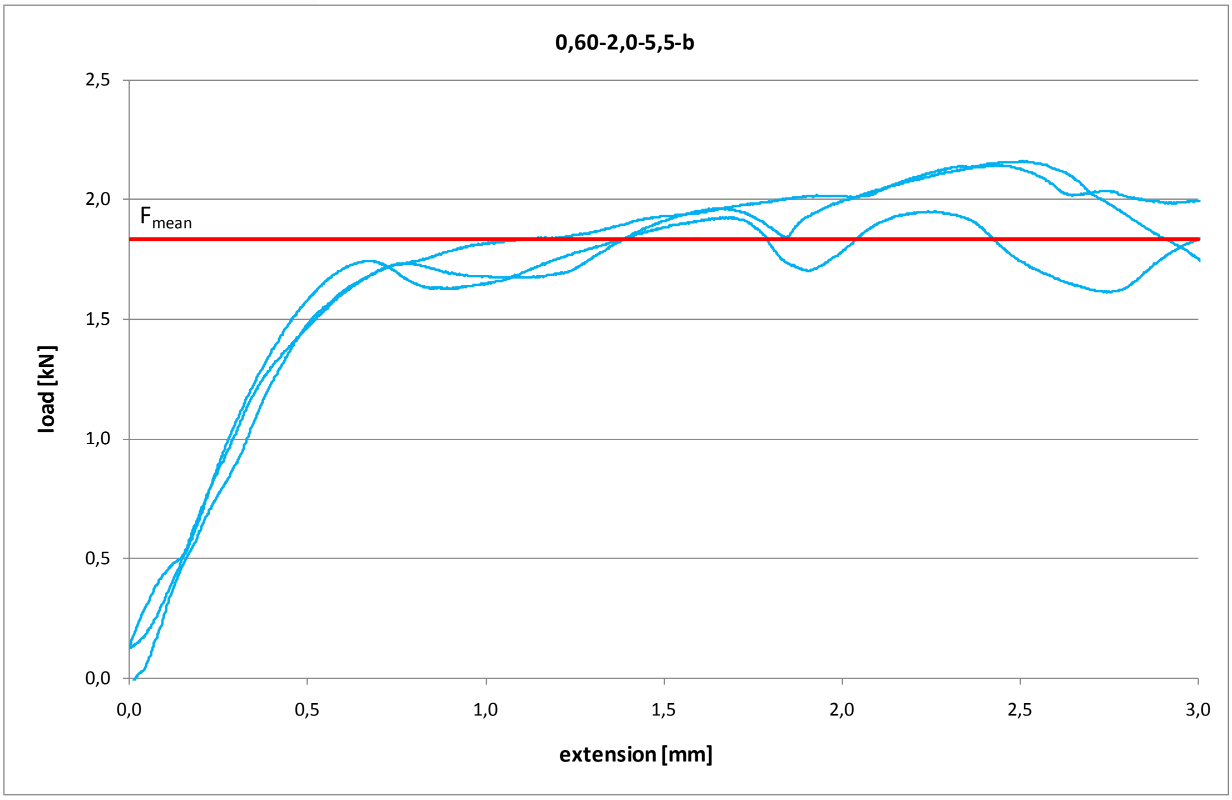


Fig. 5.7: **Comparison of lad bearing capacity**

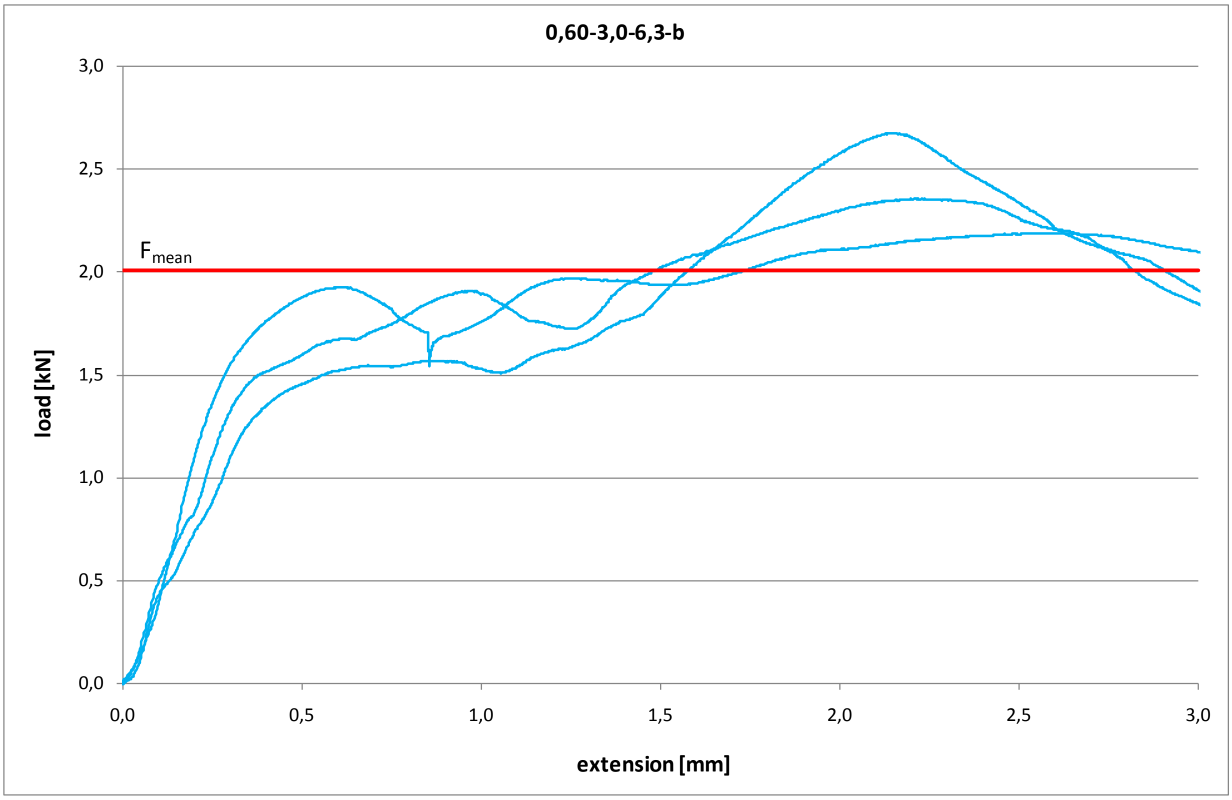


Fig. 5.8: **Comparison of lad bearing capacity**

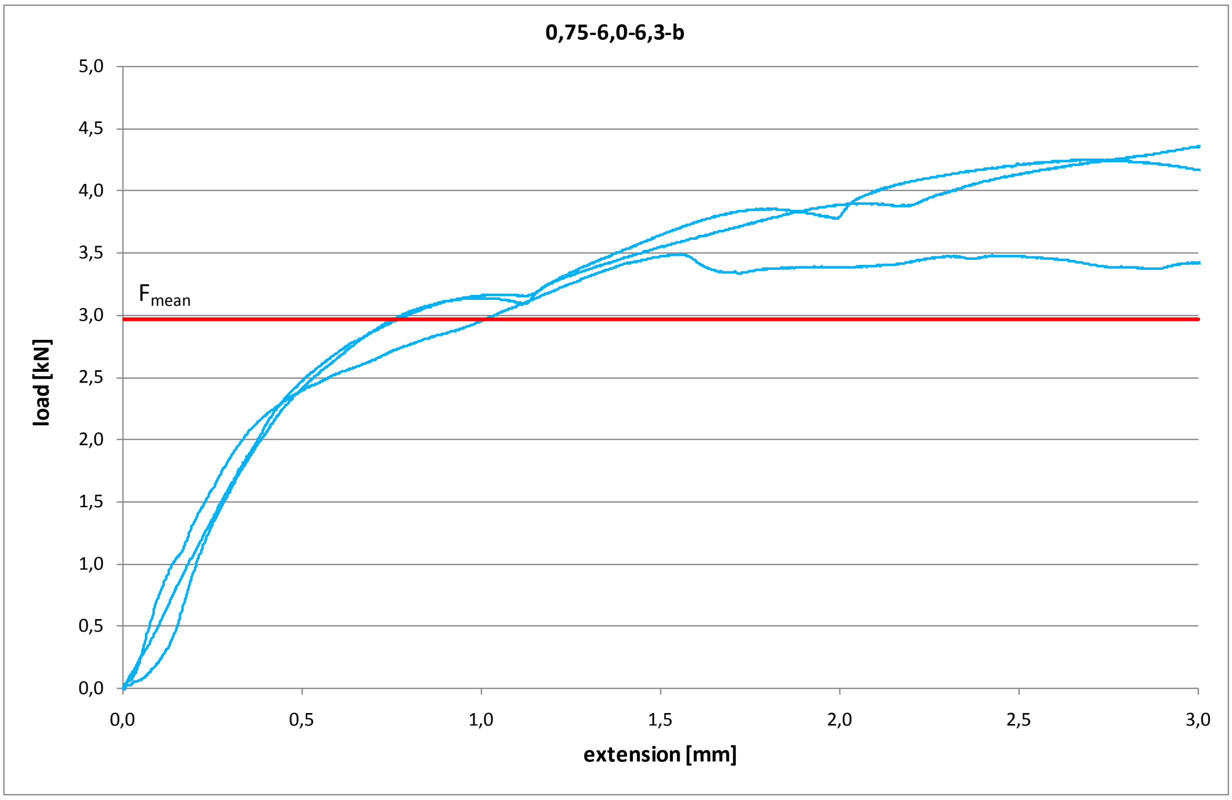


Fig. 5.9: **Comparison of lad bearing capacity**

5.5.2 Comparison with values of literature

In [11] tests to determine the stiffness of fastenings of sandwich panels are presented. Within this investigation fastenings with the following properties were tested.

Core thickness of the internal face sheet	t_{F2} = 0,67 mm
Tensile strength of the internal face sheet	$f_{u,F2}$ = 415 N/mm^2
Thickness of panel	D = 60 mm
Thickness of substructure	t_{sup} = 20 mm
Fastener	EJOT JT3-6,3xL

In the tests documented in [11] the following mean values of the stiffness are determined:

K_I = 2,43 kN/mm

K_{II} = 1,26 kN/mm

K_{III} = 1,62kN/mm

In [11] the stiffness of a fastening is defined as given in Fig. 5.10. F_{max} is the ultimate load of the particular test.

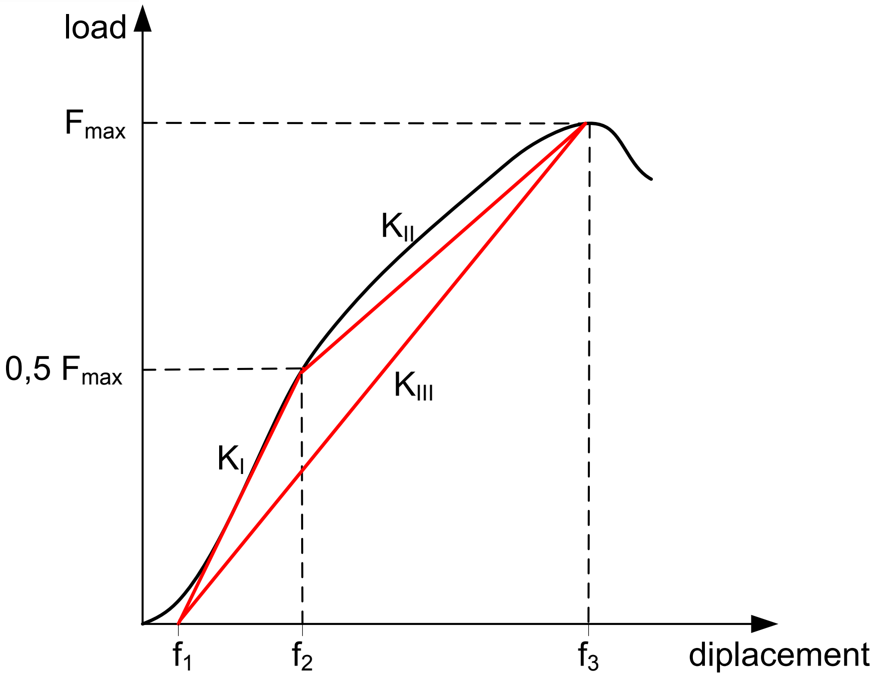


Fig. 5.10: Definition of stiffness in [11]

The stiffness K_i and k_{vi} do not correlate exactly, because they correspond to different load levels.

Calculating the stiffness k_v according to the above design model the following values ensue:

k_{vI} = 2,37 kN/mm

k_{vII} = 0,93 kN/mm

k_{vIII} = 1,70 kN/mm

There is a good agreement between the stiffness determined in the tests and by calculation, especially for the first part of the curve.

Also in [15] tests to determine the stiffness of fastenings of sandwich panels are presented. In [15] the stiffness K is determined for the initial linear part of the load-displacement curve (Fig. 5.11). So the stiffness K corresponds approximately to the stiffness k_{vI}.

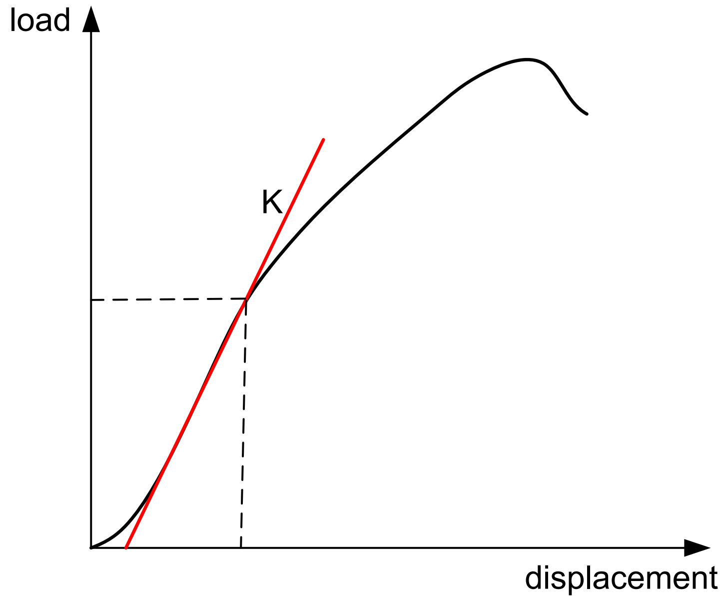


Fig. 5.11: Definition of stiffness in [15]

In [15] the fastening of a roof panel Hoesch Isodach TL 95 V and a substructure with the thickness 10 mm with a fastener JT3-6,3xL is tested. The panel has the following properties:

Core thickness of the internal face sheet	t_{F2} = 0,51 mm
Tensile strength of the internal face sheet	$f_{u,F2}$ = 462 N/mm^2
Overall depth of the panel	D = 60 mm
Thickness of the panel	D = 95 mm

For screwing the panel through the upper flange of the external face sheet (D = 95 mm) the stiffness K = 2,4 kN/mm and a corresponding calculated value of k_{vl} = 3,16 kN/mm ensue. For screwing through the lower flange (D = 60 mm) the stiffness determined in the tests is K = 3,03 kN/mm, the stiffness determined by calculation is k_{vl} = 3,17 kN/mm.

6 Stiffness and load bearing capacity of fastenings of longitudinal joints

6.1 Preliminary remarks

In addition to the connection of the panels to the substructure roof panels are also connected at longitudinal joints. Usually the load bearing capacity of this kind of fastening is determined by testing – for example according to [7] and [9]. The characteristic loads determined in the tests are given in European (e.g. [18] to [21]) or national approvals (e.g. [17]). Alternatively determination of the load bearing capacity by calculation according to EN 1993-1-3 [5] with the following formulae is possible.

$$F_{Rk} = \alpha \cdot f_u \cdot d \cdot t \qquad (6.1)$$

$t = t_{\sup}$ $\qquad$ $\alpha = 3{,}2 \cdot \sqrt{\frac{t}{d}}\ ;\ \alpha \le 2{,}1$

$t = t_{sup}$ and $t < 1{,}0mm$ $\alpha = 3{,}2 \cdot \sqrt{\frac{t}{d}}$; $\alpha \leq 2{,}1$

$t = t_{sup}$ and $t \geq 1{,}0mm$ $\alpha = 2{,}1$

$t < t_{sup} < 2{,}5 \cdot t$ determination of α by linear interpolation

For fastenings of longitudinal joints both steel sheets have the same thickness ($t = t_{F1}$). So the formulae of [5] can be reduced to

$$F_{Rk} = 3{,}2 \cdot f_{u,F1} \cdot \sqrt{d \cdot t_{F1}^3} \qquad (6.2)$$

with

t_{F1} thickness of external face sheet

$f_{u,F1}$ tensile strength of external face sheet

To get the design value of the load bearing capacity the characteristic value has to be divided by the material safety factor γ_{m2}.

$$F_{Rd} = \frac{F_{Rk}}{\gamma_{M2}} \qquad (6.3)$$

The material safety factor γ_{M2} is given by national specifications. According to EN 1993-1-3 γ_{M2} = 1,25 is recommended. If the load bearing capacity is determined by testing according to different approvals γ_{M2} = 1,33 has to be used.

Neither in the different approvals nor in [5] specifications of the stiffness of the fastenings are given. In [8] for the slip of a fastening at a longitudinal joint an approximate value of s_p = 0,25 mm/kN is given. (This corresponds to a stiffness k_v = 4,0 kN/mm.) This value is based on test results. But there are not any general models or formulae available to determine the stiffness of a fastening at a longitudinal joint.
Therefore tests on this kind of fastenings were performed. First the applicability of formula (6.2) is checked. Following general formulae to determine the stiffness of fastenings are derived.

6.2 Tests on fastenings of longitudinal joints

Tests on fastenings of longitudinal joints are performed. Because in building practice usually a sealing tape is mounted between the connected face sheets, also tests with a sealing tape are performed (Fig. 6.1). A sealing tape LS-15/2-3 (thickness 3 mm) was used.

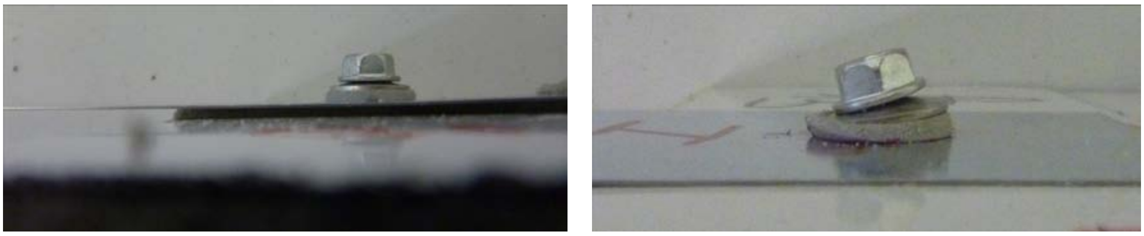


Fig. 6.1: **Fastening with and without sealing tape**

In the tests a test set up according to the ECCS-recommendations [9] and [7] is used. In each test two fastenings are tested. The test set up is given in Fig. 6.2 and Fig. 6.3.

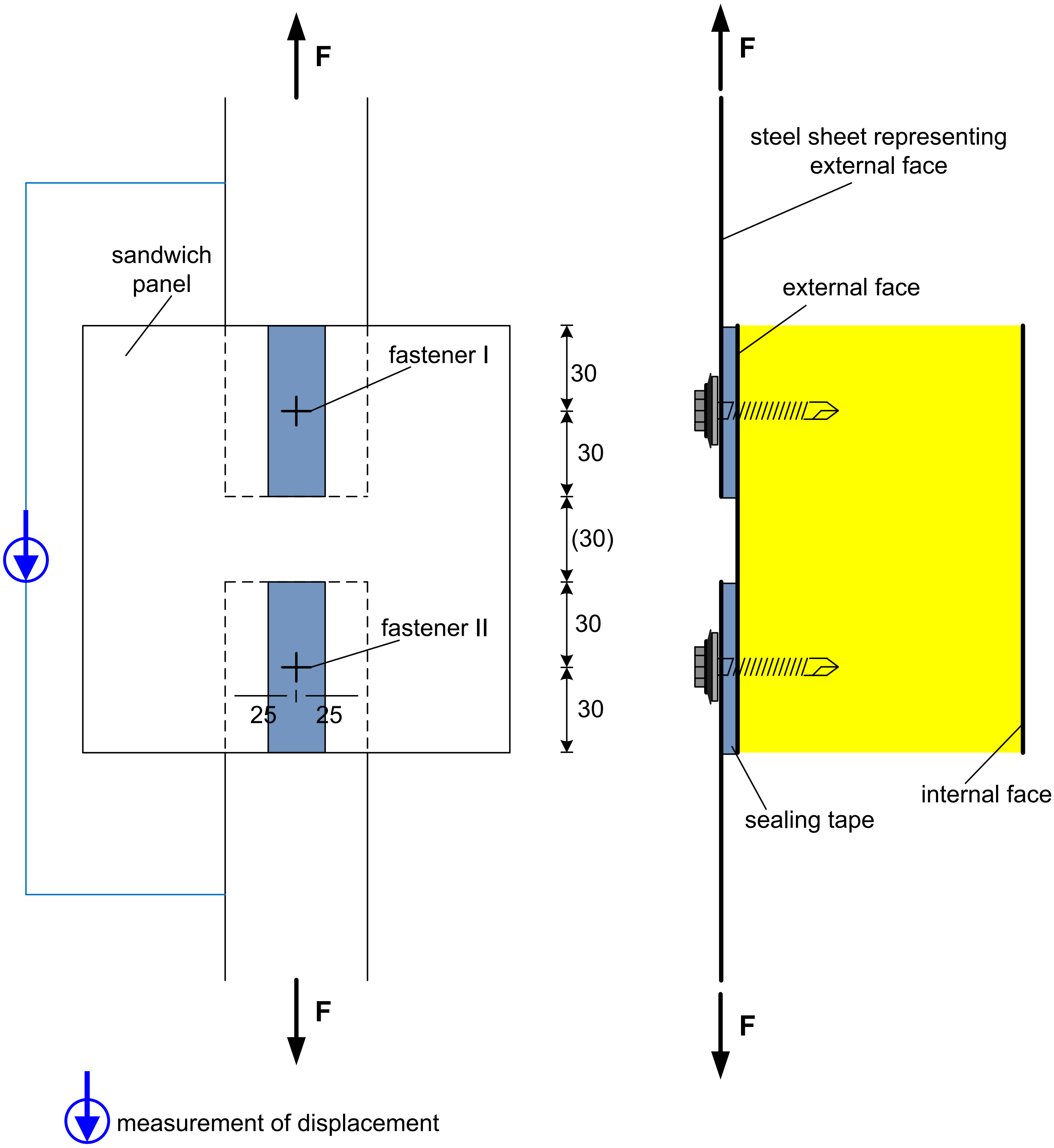


Fig. 6.2: **Test set-up of tests on fastenings of longitudinal joints**

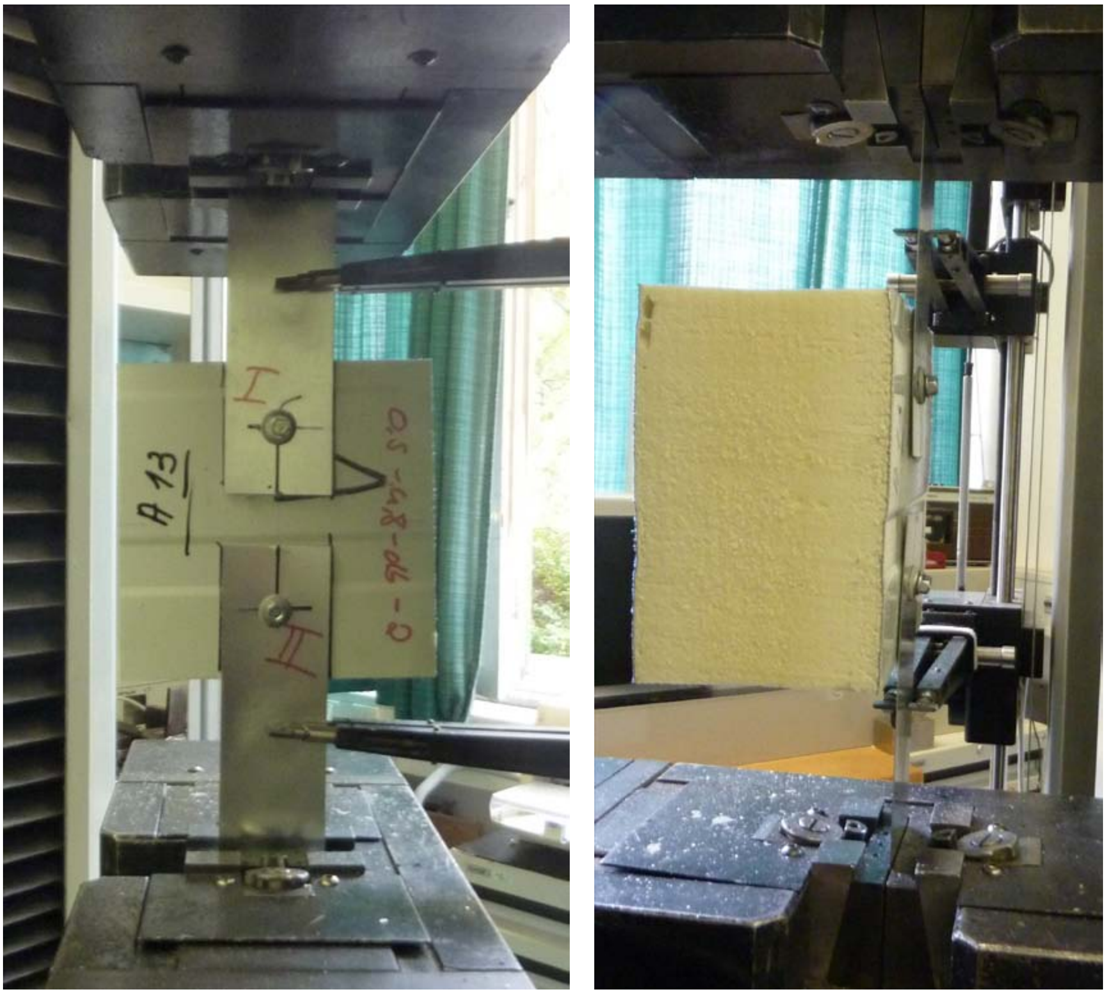


Fig. 6.3: **Test set-up of tests on fastenings of longitudinal joints**

During the tests the thickness of the face sheets as well as the nominal diameter of the fasteners are varied. Tab. 6.1 shows a compilation of the tests. The tests on longitudinal joints are documented in detail in D3.2 – part 2 [1].

No.	fastener	type of panel / thickness of steel sheets [mm]	sealing tape
0,50-4,8	SL2-S-4,8x22	A / 0,50	no
0,50-5,5	SL2-S-5,5x27	A / 0,50	no
0,50-6,3	SL2-S-L12-6,3x28	A / 0,50	no
0,75-4,8	SL2-S-4,8x22	B / 0,75	no
0,75-5,5	SL2-S-5,5x27	B / 0,75	no
0,75-6,3	SL2-S-L12-6,3x28	B / 0,75	no
0,50-4,8-st	SL2-S-4,8x22	A / 0,50	yes
0,50-5,5-st	SL2-S-5,5x27	A / 0,50	yes
0,50-6,3-st	SL2-S-L12-6,3x28	A / 0,50	yes
0,75-4,8-st	SL2-S-4,8x22	B / 0,75	yes
0,75-5,5-st	SL2-S-5,5x27	B / 0,75	yes
0,75-6,3-st	SL2-S-L12-6,3x28	B / 0,75	yes

Tab. 6.1: Compilation of tests on fastenings of longitudinal joints

6.3 Load bearing capacity

For every test the ultimate load F_{max} is determined. The ultimate load is defined to be the load at which the first decrease in load is observed in the load-displacement curve (Fig. 6.4). This definition of the ultimate load corresponds to the definition of the ultimate load given in [10]. The ultimate loads are summarised in Tab. 6.2.

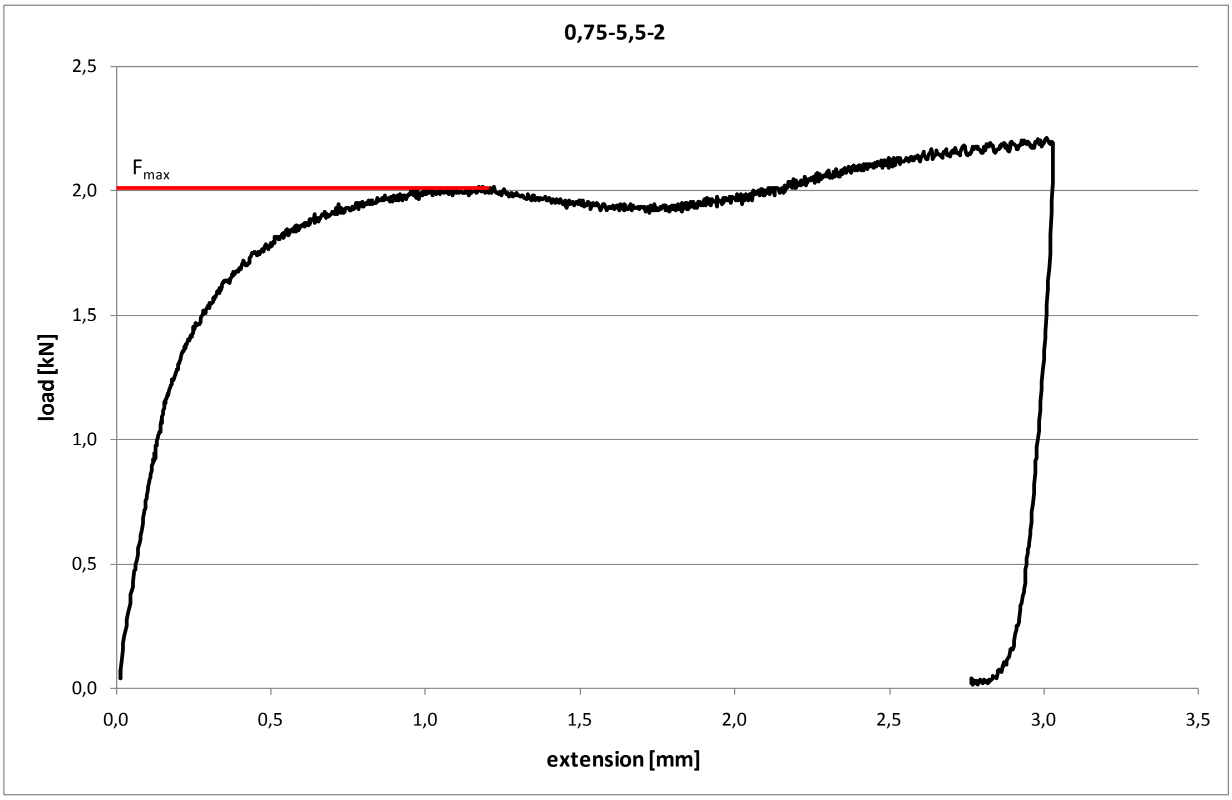


Fig. 6.4: **Example for determination of ultimate load**

core thickness of steel sheet [mm]	nominal diameter of fastener [mm]	tensile strength of steel sheet [N/mm²]	ultimate load [kN]	
			without sealing tape	with sealing tape
0,47	4,8	404	0,95	0,87
			0,80	0,87
			0,87	0,88
mean values			**0,87**	**0,87**
0,47	5,5	404	1,16	1,03
			1,02	0,99
			1,07	1,05
mean values			**1,08**	**1,02**
0,47	6,3	404	1,30	1,14
			1,05	1,17
			1,17	1,10
mean values			**1,17**	**1,14**
0,69	4,8	387	1,77	1,90
			1,49	2,00
			1,76	1,92
mean values			**1,67**	**1,94**
0,69	5,5	387	1,90	2,23
			2,02	2,05
			1,80	1,87
mean values			**1,91**	**2,05**
0,69	6,3	387	2,22	2,20
			2,19	2,18
			2,42	2,35
mean values			**2,28**	**2,24**

Tab. 6.2: Ultimate load of tests on fastenings of longitudinal joints

The results for fastenings with and without sealing tape do not show any difference in the ultimate load. Obviously the sealing tape has no or only a negligible influence on the load bearing capacity of a fastening. Therefore for the following evaluation the associated test series on fastenings with and without sealing tape are combined to one series. For every test series the mean value and the characteristic value of the ultimate load are determined (Tab. 6.3). For determination of the characteristic value the fractile factor k_n = 2.18 according to EN 1990 [4] was used.

core thickness of steel sheet [mm]	nominal diameter of fastener [mm]	tensile strength of steel sheet [N/mm²]	load bearing capacity mean value [kN]	characteristic value [kN]
0,47	4,8	404	0,87	0,77
0,47	5,5	404	1,05	0,92
0,47	6,3	404	1,16	0,97
0,69	4,8	387	1,81	1,41
0,69	5,5	387	1,98	1,64
0,69	6,3	387	2,26	2,04

Tab. 6.3: Evaluation of test results

The load bearing capacity of the fasteners used for the tests is also given in the European technical approval ETA-10/0198 [19] and in the German approval Z-14.1-4 [17]. In both approvals characteristic values for fastenings of sheets made of steel S280GD are given. The characteristic values given in approvals are determined by testing. The test results are adjusted to the nominal value of the tensile strength of steel S280GD (R_m = 360 N/mm^2) and to the minimum value of the core thickness of the steel sheets. The minimum core thickness ensues subtracting half of the tolerances given in EN 10143 [6], table 2 (standard tolerances, nominal width > 1500 mm) and the thickness of the zinc coating (0,04 mm) from the nominal value of the thickness of the steel sheet.
For comparison with the above test results the characteristic values of [19] are adjusted to the tensile strength and the core thickness measured in the tests.

$$V_{Rk,adj} = V_{Rk,ETA} \cdot \frac{R_{m,obs}}{R_m} \cdot \frac{t_{cor,obs}}{t_{cor}} \tag{6.4}$$

with

$V_{Rk,ETA}$ characteristic value given in [19]
$R_{m,obs}$ measured tensile strength
R_m nominal tensile strength of S280 (R_m = 360 N/mm^2)
$t_{cor,obs}$ measured core thickness
t_{cor} minimum value of core thickness
(t_{cor} = 0,415 mm for t = 0,50 mm; t_{cor} = 0,655 mm for t = 0,75 mm)

The characteristic values given in [19] as well as the adjusted values are given in Tab. 6.4. The test results are also recalculated with the formulae given in EN 1993-1-3 [5]. For the calculation the core thickness and the tensile strength measured in the tests is used. The calculated values are also given in Tab. 6.4.

core thick-ness of face sheet [mm]	tensile strength of face sheet [mm]	nominal diameter of fastener [N/mm²]	load bearing capacity [kN]		
			EC3	ETA	ETA ad-justed
0,47	404	4,8	0,91	0,69	0,88
0,47	404	5,5	0,98	0,75	0,95
0,47	404	6,3	1,05	0,80	1,02
0,69	387	4,8	1,56	1,26	1,43
0,69	387	5,5	1,66	1,48	1,68
0,69	387	6,3	1,78	1,55	1,76

Tab. 6.4: Comparison of load bearing capacity

In Fig. 6.5 the characteristic values determined in the tests, the adjusted values of [19] and the calculated values according to EN 1993-1-3 are compared.

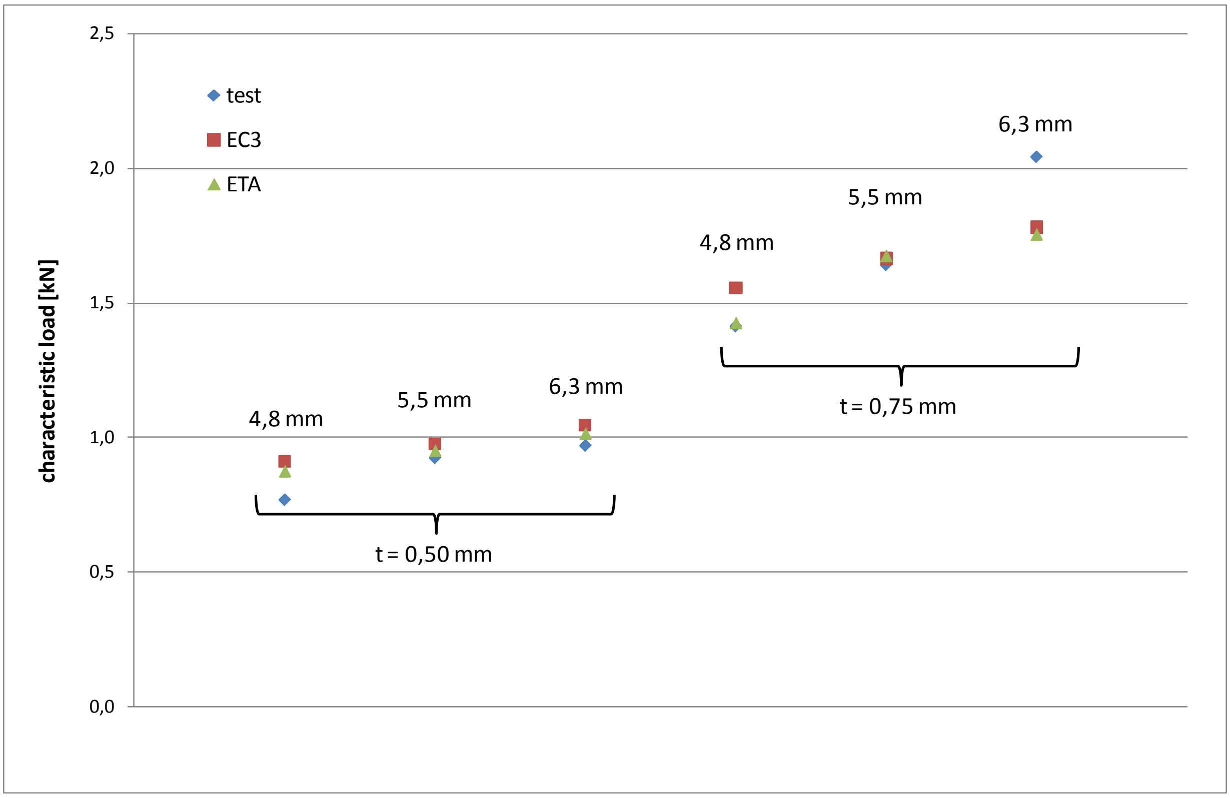


Fig. 6.5: Comparison of load bearing capacity

Fig. 6.5 shows a good agreement between the characteristic values determined by testing and by calculation according to EN 1993-1-3.

For the application range of fastenings of longitudinal joints of sandwich panels also the investigations in [16] show a good agreement between test results and the formulae given in EN

1993-1-3. (Only for fastenings of a thin sheet on a relatively thick substructure deviations of the values determined by testing and by calculation have been identified.)

For some fasteners, which are typically used for fastenings of longitudinal joints, the characteristic values given in European technical approvals [18], [19], [20], [21] (and also in the German national approval [17]) are compared to values calculated according to EN 1933-1-3 (Fig. 6.6). Aberrant from EN 1993-1-3 the tensile strength of S280GD and the minimum core thickness was used for the calculation. According to EN 1993-1-3 in most cases the nominal core thickness had to be used. The minimum core thickness was determined as given above. Also for these fasteners there is a good agreement between the characteristic values given in the approvals, which are determined by testing, and the values determined by calculation.

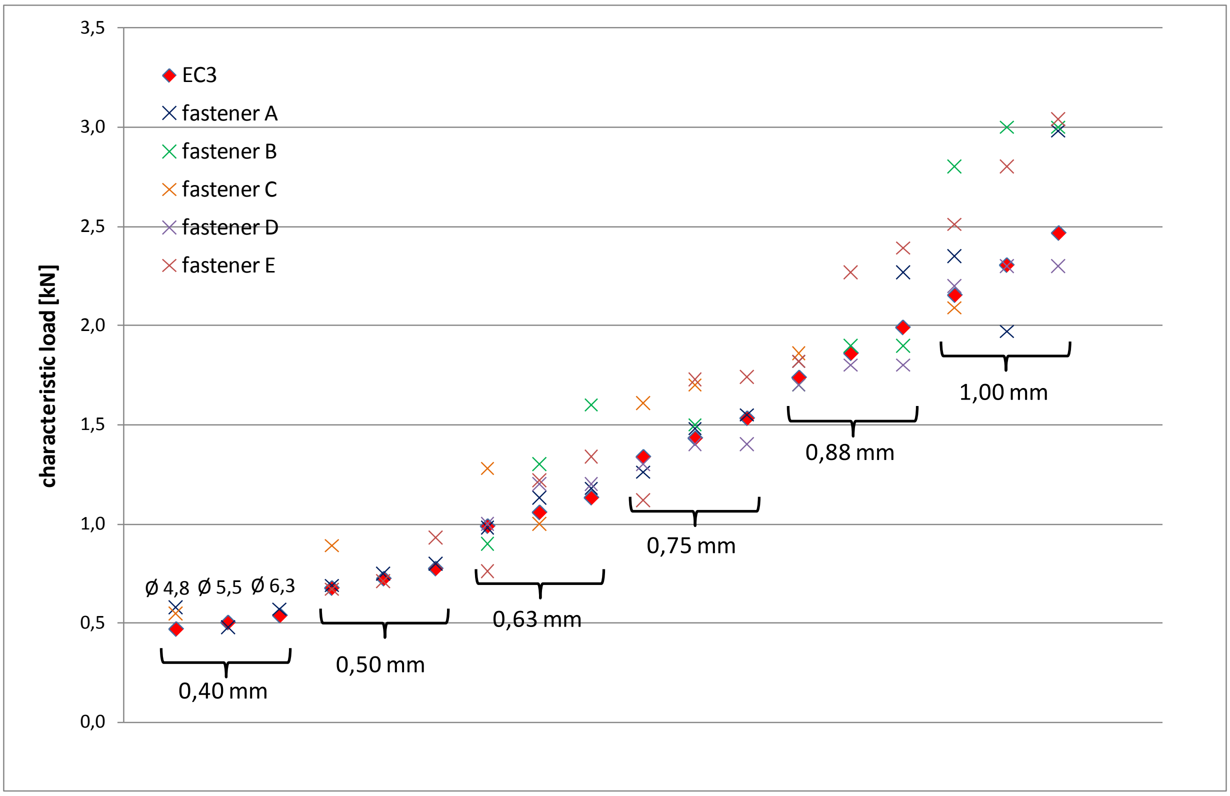


Fig. 6.6: **Comparison of load bearing capacity**

To determine the load bearing capacity of fastenings of longitudinal joints of sandwich roof panels the formulae given in EN 1993-1-3 can be used. Because both sheets have the same thickness, the formulae of the EN 1993-1-3 can be reduced to formula (6.2).

According to EN 1993-1-3 in many cases the nominal core thickness is used to calculate the load bearing capacity of a fastening. Aberrant from EN 1993-1-3 it is recommended to use the minimum core thickness of the sheeting. This was also done in the above investigations. If nominal values are used the formulae given in EN 1993-1-3 provide a too favourable load

bearing capacity. E.g. for a fastening of steel sheets with a nominal thickness of 0,4 mm the difference in the load bearing capacity is about 16%.
The tests showed that a sealing tape with a thickness up to 3 mm has no significant influence on the load bearing capacity of a fastening.

6.4 Stiffness of fastenings at longitudinal joints

6.4.1 Evaluation of tests

For the design of shear diaphragms made of sandwich panels in addition to the load bearing capacity the stiffness of the fastenings has to be known. Therefore the tests are also evaluated to derive formulae for determination of the stiffness of a fastening.
For the load-extension curves determined in the tests the displacement at the load levels $0{,}5 \cdot F_{Rk}$ and $0{,}75 \cdot F_{Rk}$ is determined. In doing so the characteristic load F_{Rk} was calculated according to (6.2). Next for both load levels the stiffness k_v of the fastening is calculated (Tab. 6.5 and Tab. 6.6).

$$k_{v0,5} = \frac{0{,}5 \cdot F_{Rk}}{f(0{,}5 \cdot F_{Rk})} \tag{6.5}$$

$$k_{v0,75} = \frac{0{,}75 \cdot F_{Rk}}{f(0{,}75 \cdot F_{Rk})} \tag{6.6}$$

sealing tape	thickness of face sheet [mm]	nominal diameter [mm]	F_{Rk} [kN]	$0,5 \cdot F_{Rk}$ [kN]	$f(0,5 \cdot F_{Rk})$ [mm]	$k_{v,0,5}$ [kN/mm]
without	0,47	4,8	0,91	0,46	0,09	5,07
without	0,47	4,8	0,91	0,46	0,10	4,56
without	0,47	4,8	0,91	0,46	0,08	5,70
without	0,47	5,5	0,98	0,49	0,10	4,88
without	0,47	5,5	0,98	0,49	0,10	4,88
without	0,47	6,3	1,05	0,52	0,10	5,23
without	0,47	6,3	1,05	0,52	0,09	5,81
without	0,69	4,8	1,56	0,78	0,11	7,07
without	0,69	4,8	1,56	0,78	0,14	5,55
without	0,69	5,5	1,66	0,83	0,13	6,40
without	0,69	5,5	1,66	0,83	0,11	7,57
without	0,69	6,3	1,78	0,89	0,11	8,10
without	0,69	6,3	1,78	0,89	0,11	8,10
with	0,47	4,8	0,91	0,46	0,13	3,51
with	0,47	4,8	0,91	0,46	0,14	3,26
with	0,47	5,5	0,98	0,49	0,12	4,07
with	0,47	5,5	0,98	0,49	0,11	4,44
with	0,47	6,3	1,05	0,52	0,09	5,81
with	0,47	6,3	1,05	0,52	0,09	5,81
with	0,69	4,8	1,56	0,78	0,12	6,48
with	0,69	4,8	1,56	0,78	0,17	4,57
with	0,69	5,5	1,66	0,83	0,10	8,32
with	0,69	5,5	1,66	0,83	0,10	8,32
with	0,69	6,3	1,78	0,89	0,10	8,91
with	0,69	6,3	1,78	0,89	0,10	8,91
with	0,69	6,3	1,78	0,89	0,11	8,10

Tab. 6.5: Determination of stiffness k_v at load level $0,5 \cdot F_{Rk}$

sealing tape	thickness of face sheet [mm]	nominal diameter [mm]	F_{Rk} [kN]	$0,75 \cdot F_{Rk}$ [kN]	$f(0,75 \cdot F_{Rk})$ [mm]	$k_{v,0,75}$ [kN/mm]
without	0,47	4,8	0,91	0,68	0,16	4,28
without	0,47	4,8	0,91	0,68	0,17	4,03
without	0,47	4,8	0,91	0,68	0,16	4,28
without	0,47	5,5	0,98	0,73	0,15	4,88
without	0,47	5,5	0,98	0,73	0,18	4,07
without	0,47	6,3	1,05	0,78	0,18	4,36
without	0,47	6,3	1,05	0,78	0,18	4,36
without	0,69	4,8	1,56	1,17	0,19	6,14
without	0,69	4,8	1,56	1,17	0,28	4,17
without	0,69	5,5	1,66	1,25	0,25	4,99
without	0,69	5,5	1,66	1,25	0,17	7,34
without	0,69	6,3	1,78	1,34	0,20	6,68
without	0,69	6,3	1,78	1,34	0,19	7,03
with	0,47	4,8	0,91	0,68	0,22	3,11
with	0,47	4,8	0,91	0,68	0,23	2,98
with	0,47	5,5	0,98	0,73	0,21	3,49
with	0,47	5,5	0,98	0,73	0,18	4,07
with	0,47	6,3	1,05	0,78	0,17	4,61
with	0,47	6,3	1,05	0,78	0,17	4,61
with	0,69	4,8	1,56	1,17	0,23	5,07
with	0,69	4,8	1,56	1,17	0,26	4,49
with	0,69	5,5	1,66	1,25	0,22	5,67
with	0,69	5,5	1,66	1,25	0,25	4,99
with	0,69	6,3	1,78	1,34	0,17	7,86
with	0,69	6,3	1,78	1,34	0,16	8,35

Tab. 6.6: Determination of stiffness k_v at load level $0,75 \cdot F_{Rk}$

As for the load bearing capacity there is no significant difference in the stiffness of fastenings with and without sealing tape. So the associated test series for fastenings with and without sealing tape are combined to one series. The stiffness is approximately linearly dependent on the core thickness of the steel sheet and on the nominal diameter of the screw fastener. The linear dependency is shown in Fig. 6.7, where the mean values of the quotients k_v/t are opposed to the nominal diameter of the fastener.

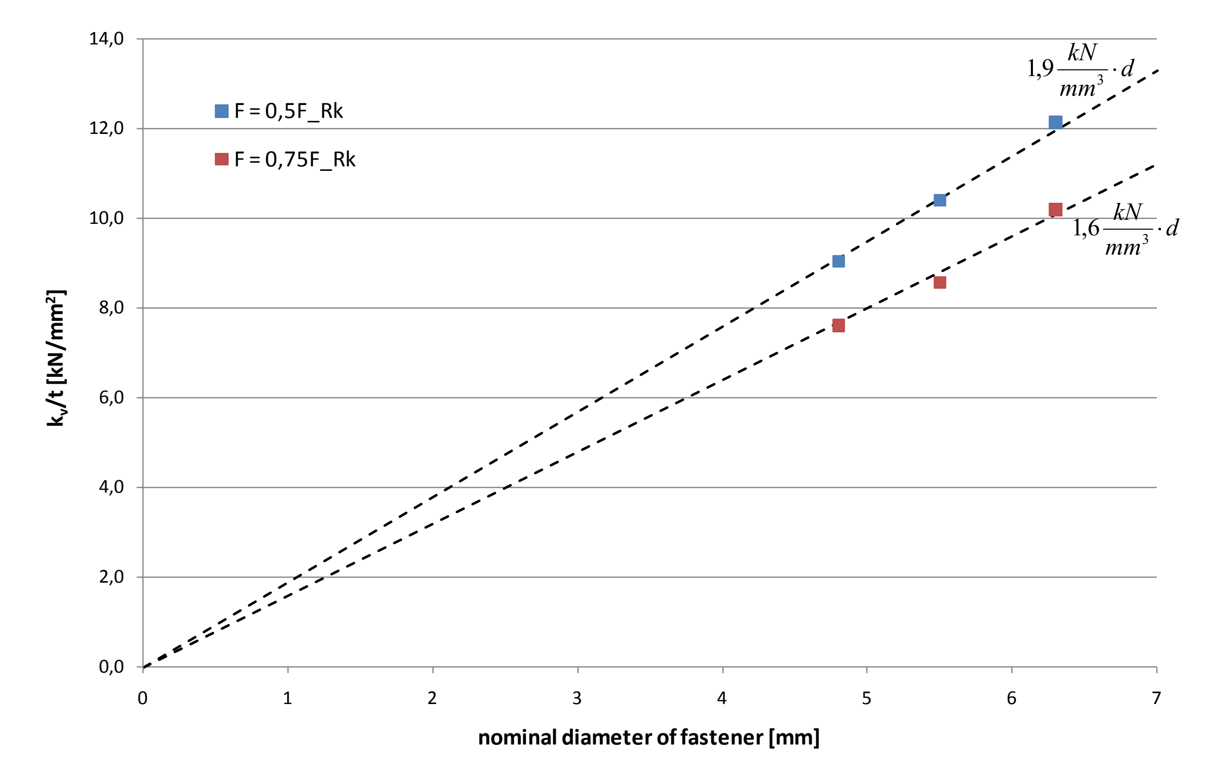


Fig. 6.7: Dependency of stiffness on thickness and diameter

Because of the linear dependency on the sheet thickness t and the nominal diameter d the stiffness k_v of a fastening can be calculated with

$$k_v = A \cdot t \cdot d \tag{6.7}$$

with

A constant factor [N/mm³] (determined below)

In Tab. 6.7 and Tab. 6.8 the factor A is re-calculated. The mean values of the constant factors A are

$$A_{0,5} = 1900 N / mm^3 \tag{6.8}$$

$$A_{0,75} = 1600 N / mm^3 \tag{6.9}$$

So the stiffness of fastenings at longitudinal joints can be calculated by the following formulae.

$$k_{v0,5} = 1900 \frac{N}{mm^3} \cdot t_{F1} \cdot d \tag{6.10}$$

$$k_{v0,75} = 1600 \frac{N}{mm^3} \cdot t_{F1} \cdot d \tag{6.11}$$

For comparison the calculated values are also presented in Fig. 6.7.

sealing tape	core thickness of face sheet t [mm]	nominal diameter d [mm]	$k_{v0,5}$ [kN/mm]	$\frac{k_{v0,5}}{t}$ [kN/mm²]	$A = \frac{k_{v0,5}}{t \cdot d}$ [kN/mm³]
without	0,47	4,8	5,07	10,79	2,25
without	0,47	4,8	4,56	9,71	2,02
without	0,47	4,8	5,70	12,14	2,53
with	0,47	4,8	3,51	7,47	1,56
with	0,47	4,8	3,26	6,93	1,44
without	0,69	4,8	7,07	10,24	2,13
without	0,69	4,8	5,55	8,05	1,68
with	0,69	4,8	6,48	9,39	1,96
with	0,69	4,8	4,57	6,63	1,38
mean value				9,04	1,88
without	0,47	5,5	4,88	10,39	1,89
without	0,47	5,5	4,88	10,39	1,89
with	0,47	5,5	4,07	8,66	1,57
with	0,47	5,5	4,44	9,45	1,72
without	0,69	5,5	6,40	9,28	1,69
without	0,69	5,5	7,57	10,97	1,99
with	0,69	5,5	8,32	12,06	2,19
with	0,69	5,5	8,32	12,06	2,19
mean value				10,41	1,89
without	0,47	6,3	5,23	11,12	1,77
without	0,47	6,3	5,81	12,36	1,96
with	0,47	6,3	5,81	12,36	1,96
with	0,47	6,3	5,81	12,36	1,96
without	0,69	6,3	8,10	11,74	1,86
without	0,69	6,3	8,10	11,74	1,86
with	0,69	6,3	8,91	12,91	2,05
with	0,69	6,3	8,91	12,91	2,05
with	0,69	6,3	8,10	11,74	1,86
mean value				12,14	1,93

Tab. 6.7: Determination of constant factor A at load level $0,5 \cdot F_{Rk}$

sealing tape	thickness of face sheet t [mm]	nominal diameter D [mm]	$k_{v0,75}$ [kN/mm]	$\frac{k_{v0,75}}{t}$ [kN/mm²]	$A = \frac{k_{v0,75}}{t \cdot d}$ [kN/mm³]
without	0,47	4,8	4,28	9,10	1,90
without	0,47	4,8	4,03	8,57	1,78
without	0,47	4,8	4,28	9,10	1,90
with	0,47	4,8	3,11	6,62	1,38
with	0,47	4,8	2,98	6,33	1,32
without	0,69	4,8	6,14	8,90	1,85
without	0,69	4,8	4,17	6,04	1,26
with	0,69	4,8	5,07	7,35	1,53
with	0,69	4,8	4,49	6,50	1,35
mean value				7,61	1,59
without	0,47	5,5	4,88	10,39	1,89
without	0,47	5,5	4,07	8,66	1,57
with	0,47	5,5	3,49	7,42	1,35
with	0,47	5,5	4,07	8,66	1,57
without	0,69	5,5	4,99	7,24	1,32
without	0,69	5,5	7,34	10,64	1,94
with	0,69	5,5	5,67	8,22	1,50
with	0,69	5,5	4,99	7,24	1,32
mean value				8,56	1,56
without	0,47	6,3	4,36	9,27	1,47
without	0,47	6,3	4,36	9,27	1,47
with	0,47	6,3	4,61	9,81	1,56
with	0,47	6,3	4,61	9,81	1,56
without	0,69	6,3	6,68	9,68	1,54
without	0,69	6,3	7,03	10,19	1,62
with	0,69	6,3	7,86	11,39	1,81
with	0,69	6,3	8,35	12,10	1,92
mean value				10,19	1,62

Tab. 6.8: Determination of constant factor A at load level $0{,}75 \cdot F_{Rk}$

The load level $0{,}5 \cdot F_{Rk}$ is within the linear part of the load-displacement curve. At the load level $0{,}75 \cdot F_{Rk}$ the nonlinear part of the curve is already achieved. Usually the stiffness of a fastening has to be determined for serviceability loads [8], [9], [12]. To be approximately on the level of serviceability loads the stiffness $k_{v0,5}$ should be used for design purposes.

$$k_v = k_{v0,5} = 1900 \frac{N}{mm^3} \cdot t_{F1} \cdot d \tag{6.12}$$

6.4.2 Verification

For verification of the above formula the calculated stiffness is compared to some load-displacement curves determined by testing of fastenings with different screw fasteners. For the tests a test set-up according to [7], [9] is used (Fig. 6.8). The test set-up differs from the above test set-up. Only one fastening is considered per test.

Tab. 6.9 shows a compilation of the tests. Also the calculated stiffness k_v is given in Tab. 6.9. For calculation of the stiffness the core thickness measured in the tests was used.

No.	nominal diameter of fastener [mm]	diameter of sealing washer [mm]	thickness of steel sheet [mm]	$k_{v0,5}$ [kN/mm]
A-1	4,8	-	0,470	4,29
A-2	4,8	-	0,560	5,11
A-3	4,8	-	0,670	6,11
B-1	4,8	9,5	0,441	4,02
B-2	4,8	9,5	0,699	6,37
B-3	4,8	9,5	0,972	8,86
C-1	5,5	14	0,392	4,10
C-2	5,5	14	0,470	4,91
C-3	5,5	14	0,684	7,15
C-4	5,5	14	0,984	10,28
D-1	5,5	13	0,391	4,09
D-2	5,5	13	0,477	4,98
E-1	6,3	EPDM-sealing ring	0,393	4,70
E-2	6,3	EPDM-sealing ring	0,701	8,39
E-3	6,3	EPDM-sealing ring	1,177	14,09
F-1	6,3	11	0,476	5,70
F-2	6,3	11	0,714	8,55
F-3	6,3	11	0,989	11,84
F-4	6,3	11	1,187	14,21

Tab. 6.9: Compilation of tests for verification

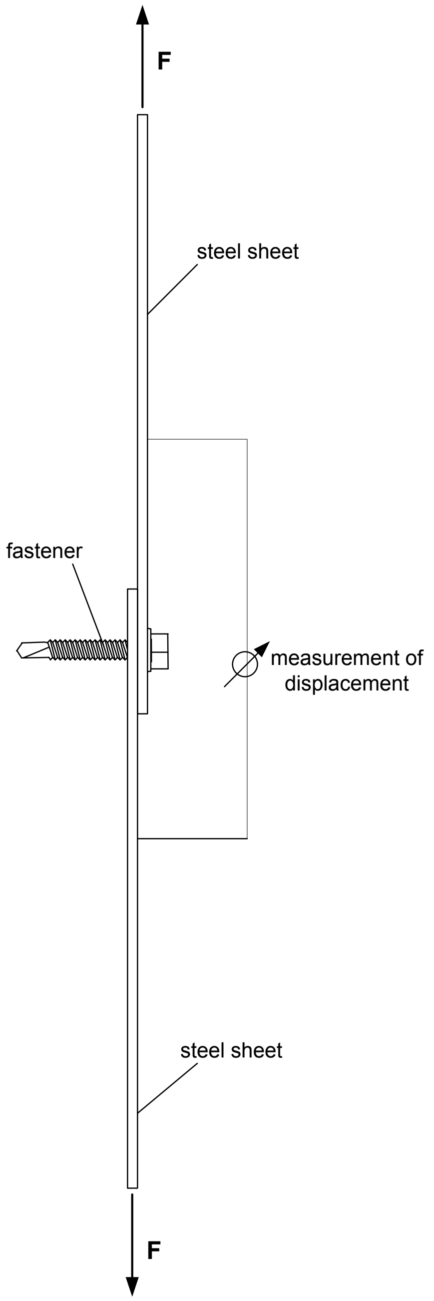


Fig. 6.8: Tests set-up

In Annex 3 the load-displacement curves determined in the tests are presented. Also the calculated stiffness $k_{v0,5}$, which approximately corresponds to the linear part of the curve is given in the diagrams. The stiffness determined by calculation fits well to the test results. Only for test series A-1 to A-3 a significant deviation occurred. The behaviour of the tested fastenings is stiffer than calculated. A possible reason for this stiff behaviour is that fastenings without sealing washer were tested.

7 Determination of the stiffness of fastenings by testing

With the above formulae the stiffness of fastenings of sandwich panels can approximately be determined by calculation. It is also possible to determine the stiffness of fastenings by testing. For tests on fastenings of sandwich panels and steel substructures a test set-up according to Fig. 4.17 is recommended. For tests on fastenings of longitudinal joints a tests set-up according to Fig. 6.2 or alternatively the test set-up according to Fig. 6.8 can be used. The displacement has to be measured using an extensometer.
For every test the displacement $f(F_{WL})$ corresponding to the expected working load F_{WL} has to be determined. The maximum working load can be assumed to be approximately half of the characteristic load. For calculation of the stiffness k_v the mean value $f(F_{WL})_{mean}$ of displacements is used.

$$k_v = \frac{F_{WL}}{f(F_{WL})_{mean}} = \frac{0,5 \cdot F_{Rk}}{f(0,5 \cdot F_{Rk})_{mean}} \tag{7.1}$$

If two fasteners are tested in one test (Fig. 4.17, Fig. 6.2), the measured displacement has to be divided by two.

8 Summary

In addition to the load bearing capacity of fastenings of sandwich panels sometimes also the stiffness of fastenings has to be known – e.g. to design shear diaphragms made of sandwich panels. For both, load bearing capacity and stiffness of fastenings of sandwich panels, no general calculation method exists. For each single case experimental investigations are necessary.
In D3.3 – part 3 formulae to determine the stiffness of the single components of a fastening are derived. A mechanical model to determine the load bearing capacity and the stiffness of fastenings of sandwich panels to a steel substructure is presented. In addition fastenings of longitudinal joints of roof panels have been investigated. Also for the stiffness of these fastenings a general formula was derived.
A summary of the formulae, which can be used for the design of fastenings of sandwich panels, is presented in Annex 4.

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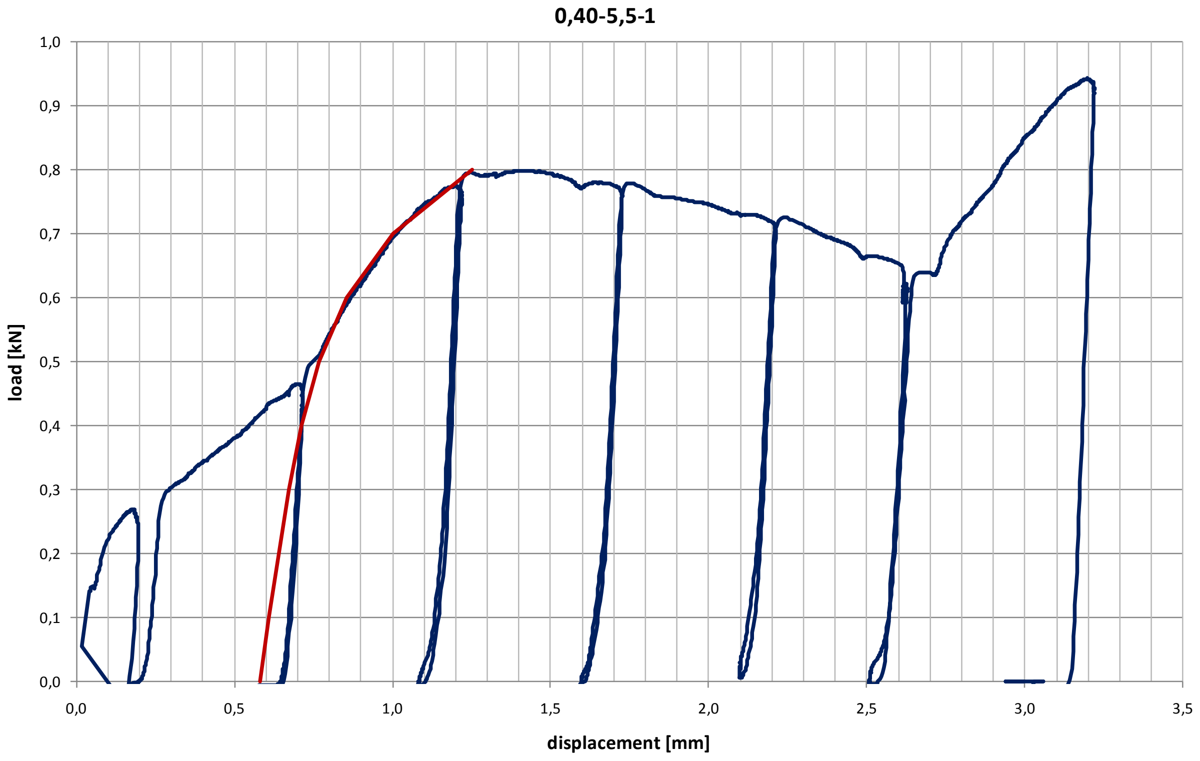
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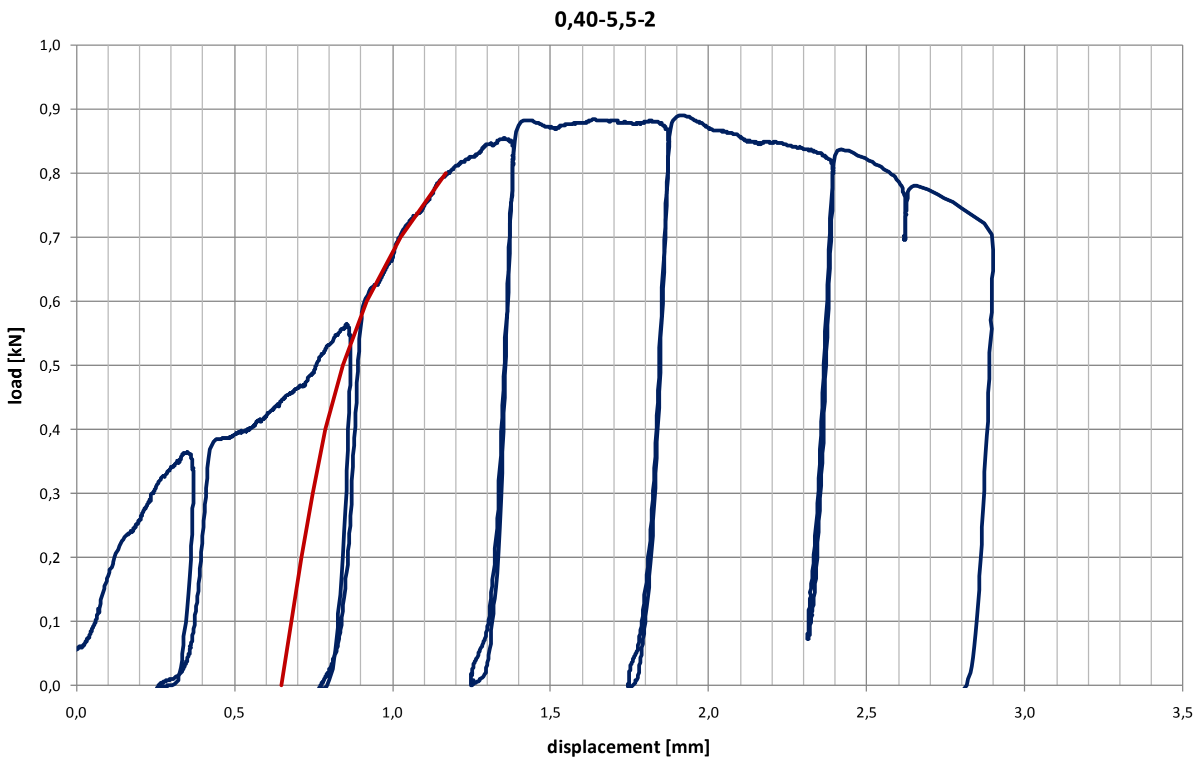
displacement [mm]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load [kN]
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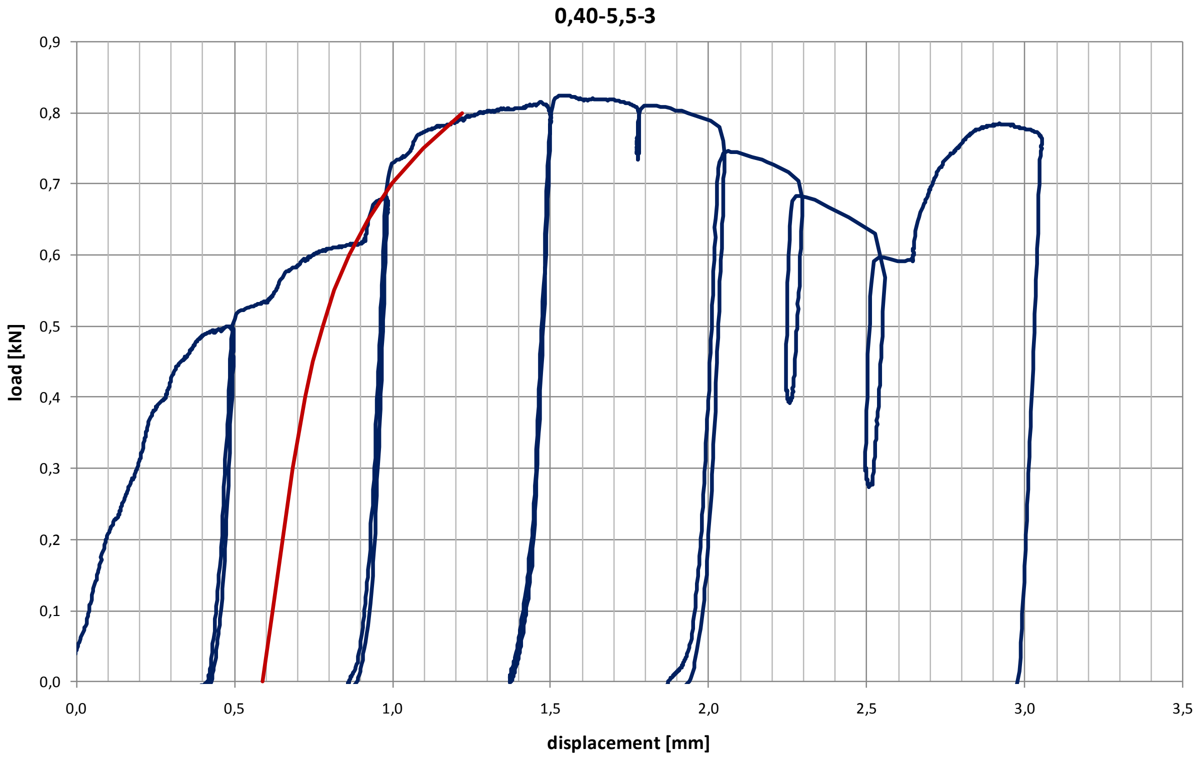
3,5
displacement [mm]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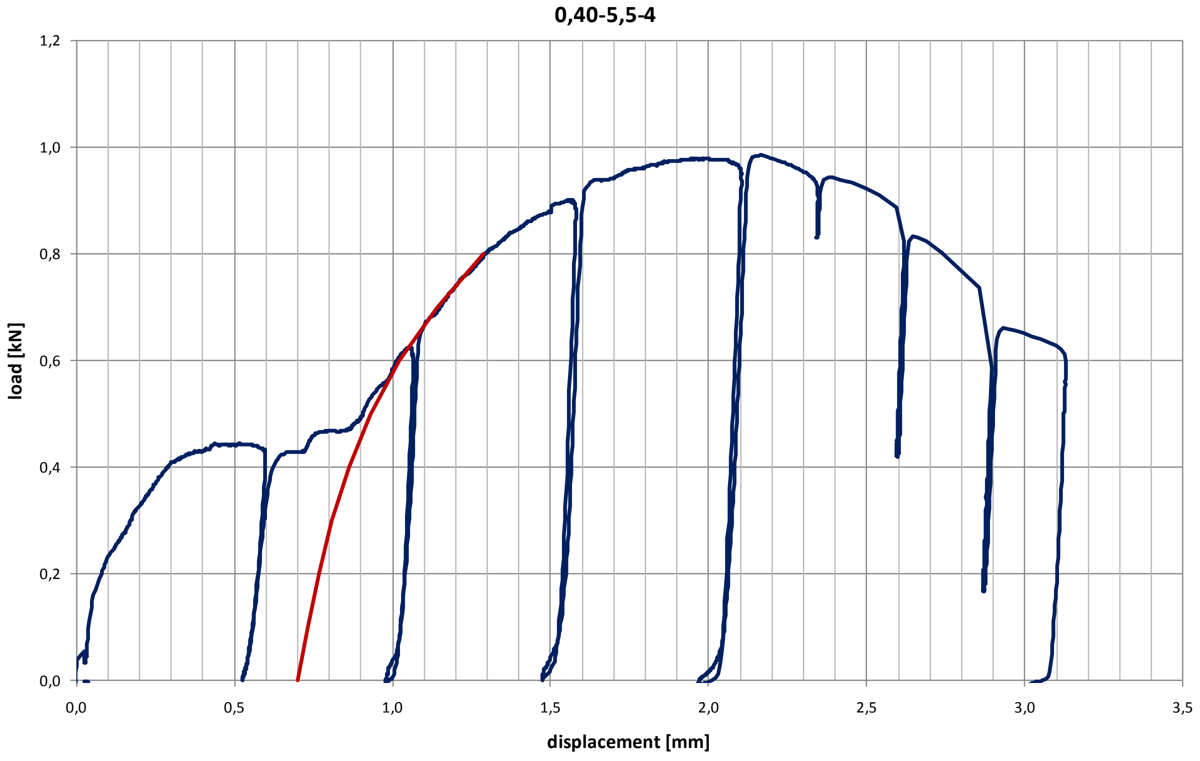
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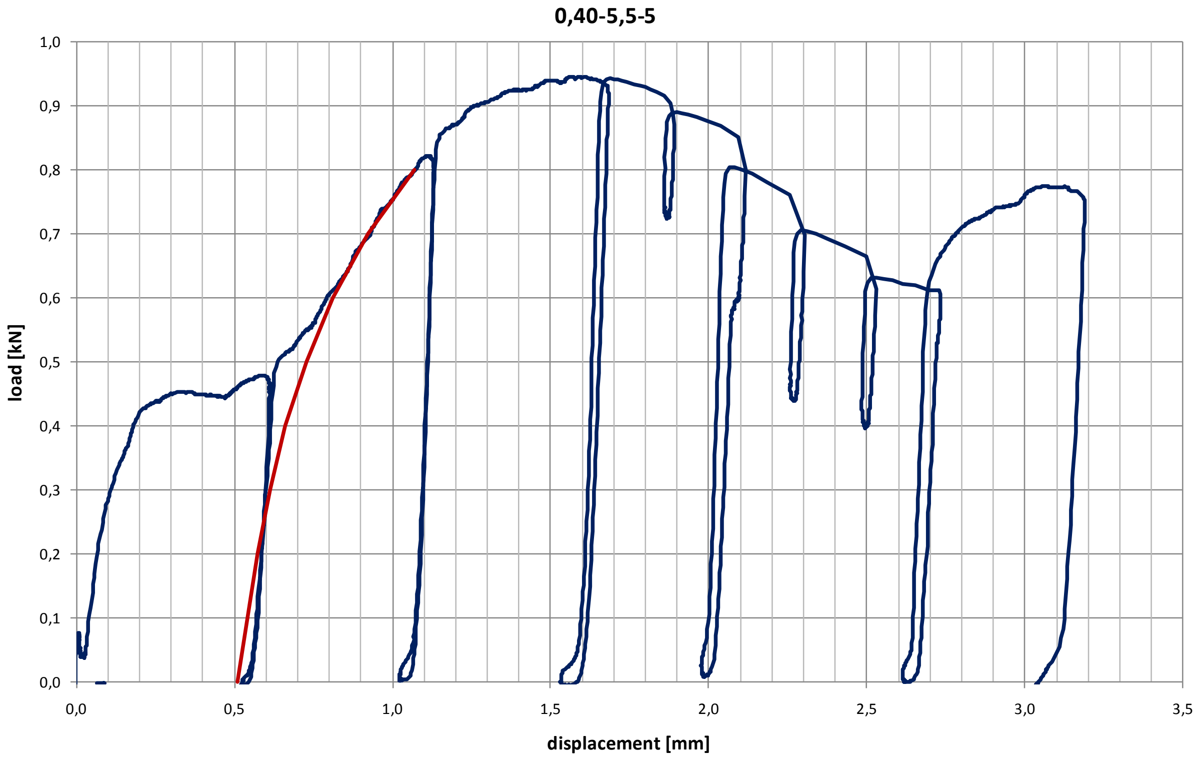
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displacement [mm]
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0,8
0,7
0,6
0,5
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0,3
0,2
0,1
0,0
0,5
1,0
1,5
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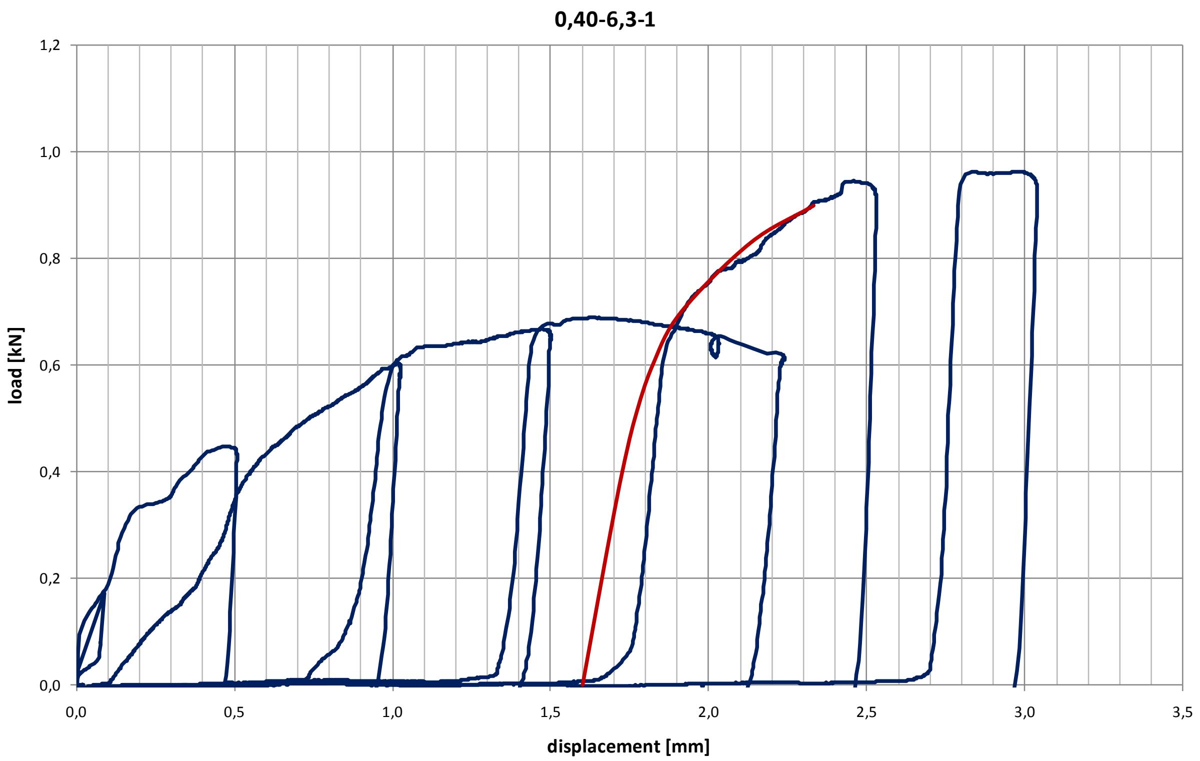
3,0
3,5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0,2
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1,0
1,5
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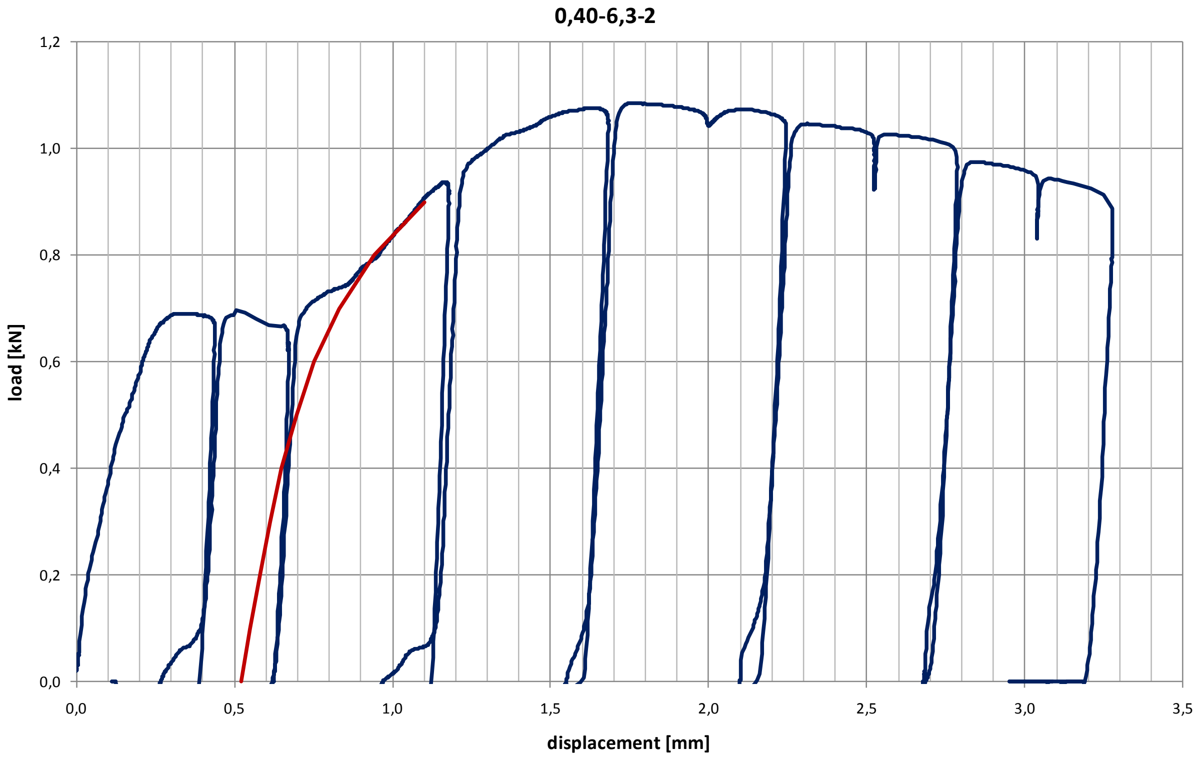
2,5
3,0
3,5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1,0
0,8
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0,2
0,0
0,0
0,5
1,0
1,5
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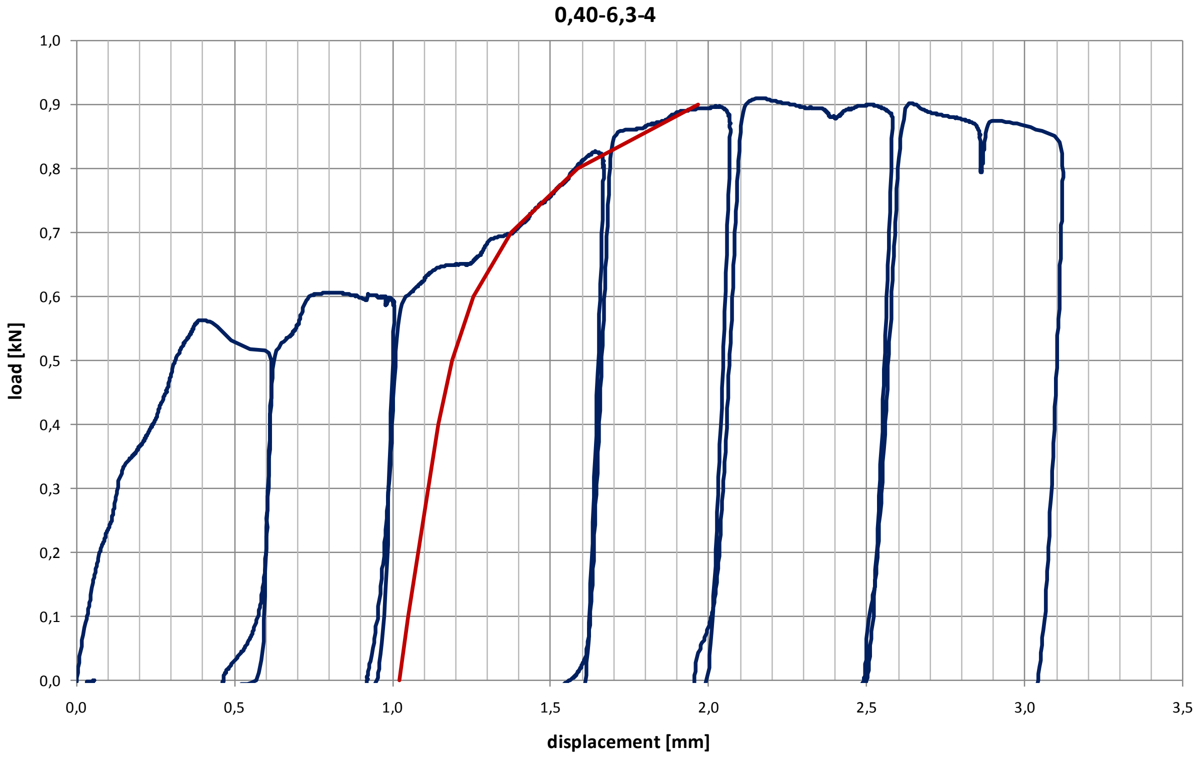
2,5
3,0
3,5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load [kN]
displacement [mm]
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0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
0,0
0,5
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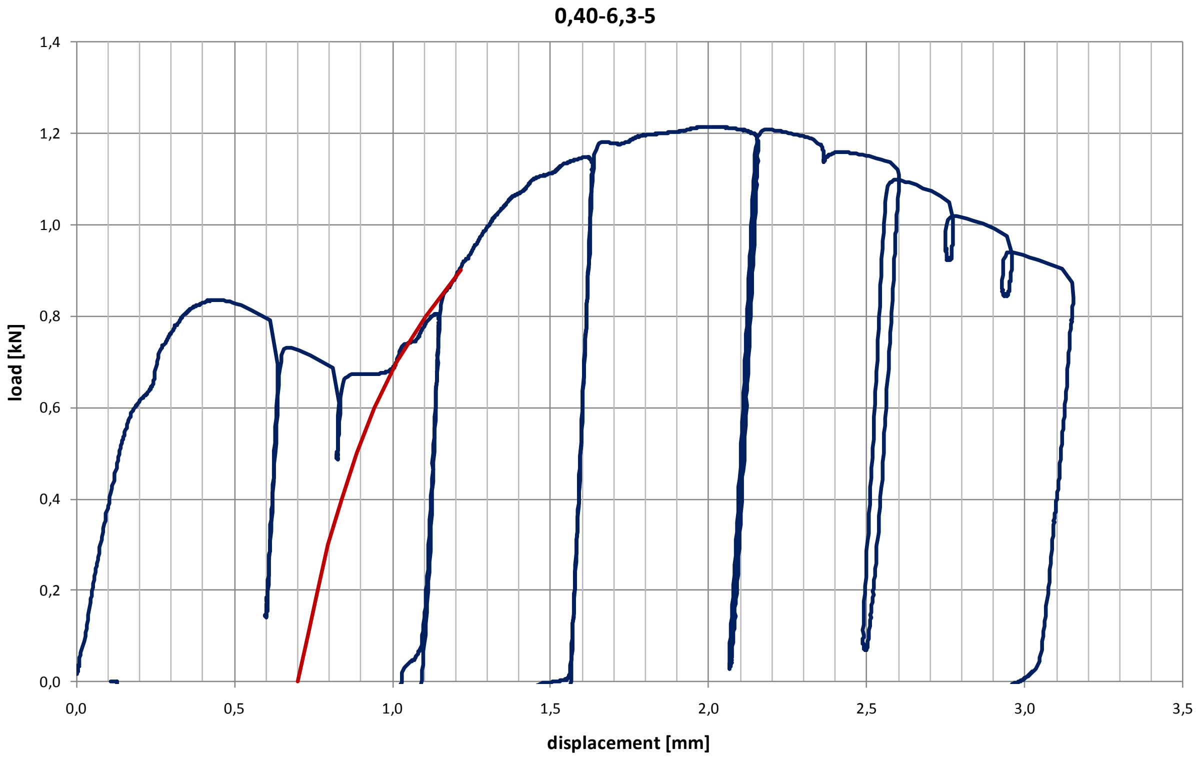
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load [kN]
displacement [mm]
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0,2
0,4
0,6
0,8
1,0
1,2
1,4
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0,5
1,0
1,5
2,0
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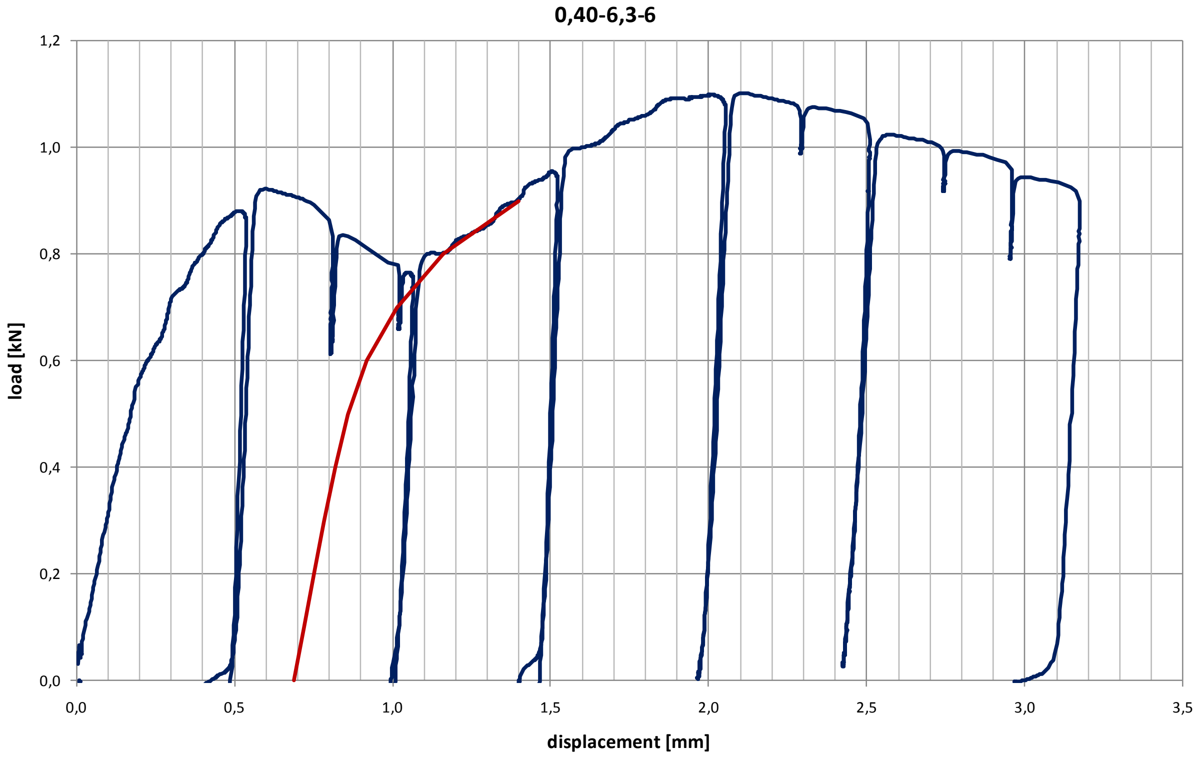
3,5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0,2
0,4
0,6
0,8
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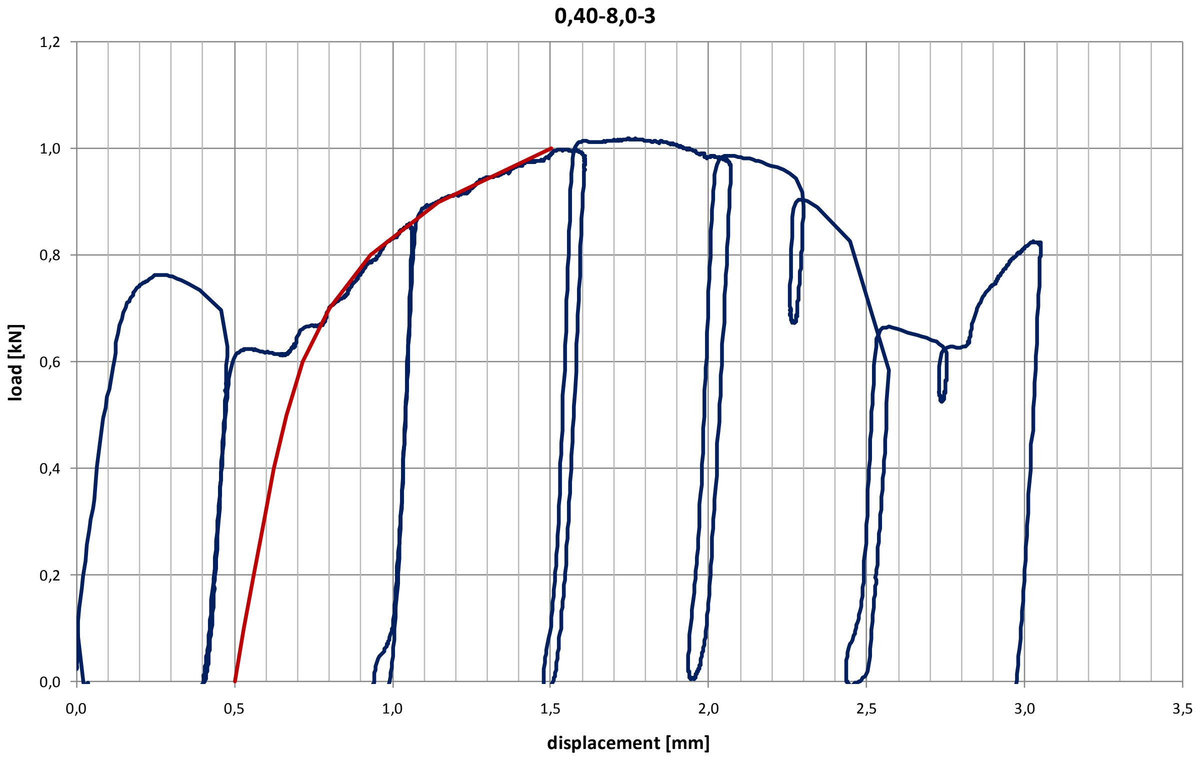
0,5
1,0
1,5
2,0
2,5
3,0
3,5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0,2
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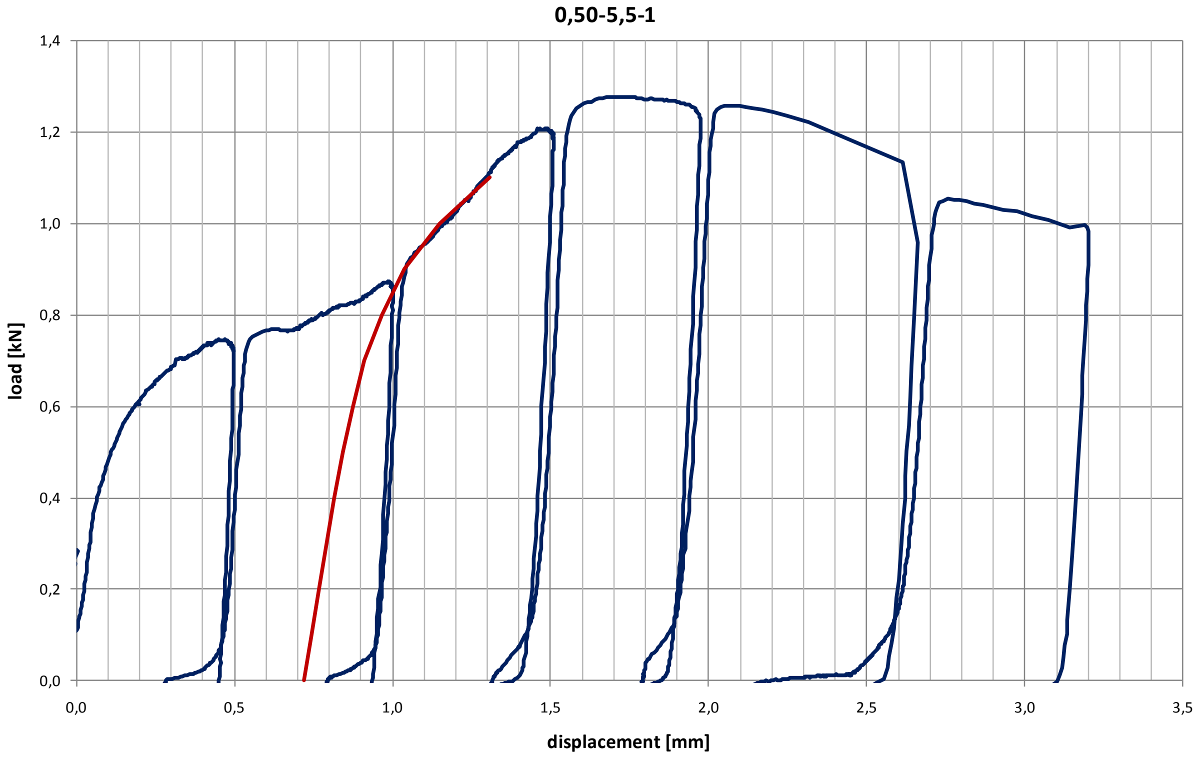
1,0
1,5
2,0
2,5
3,0
3,5
displacement [mm]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1,4
1,2
1,0
0,8
0,6
0,4
0,2
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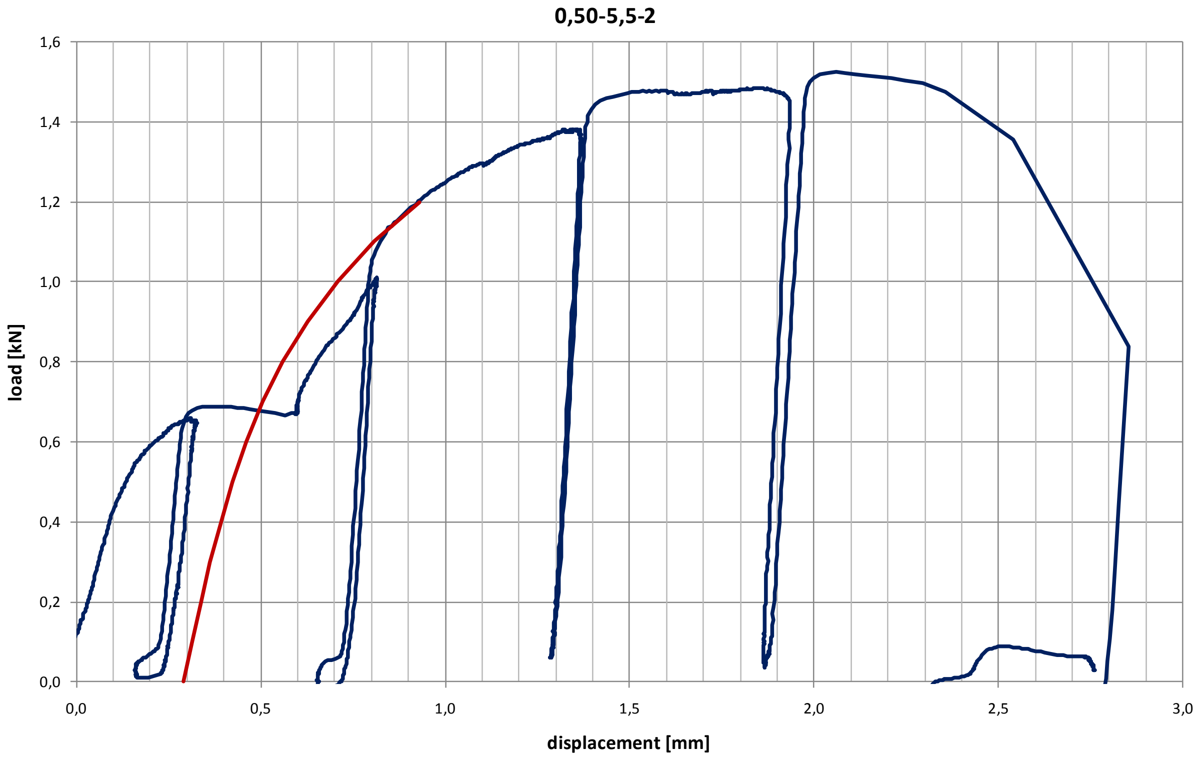
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5
displacement [mm]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displacement [mm]
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1,4
1,2
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0,2
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0,0
0,5
1,0
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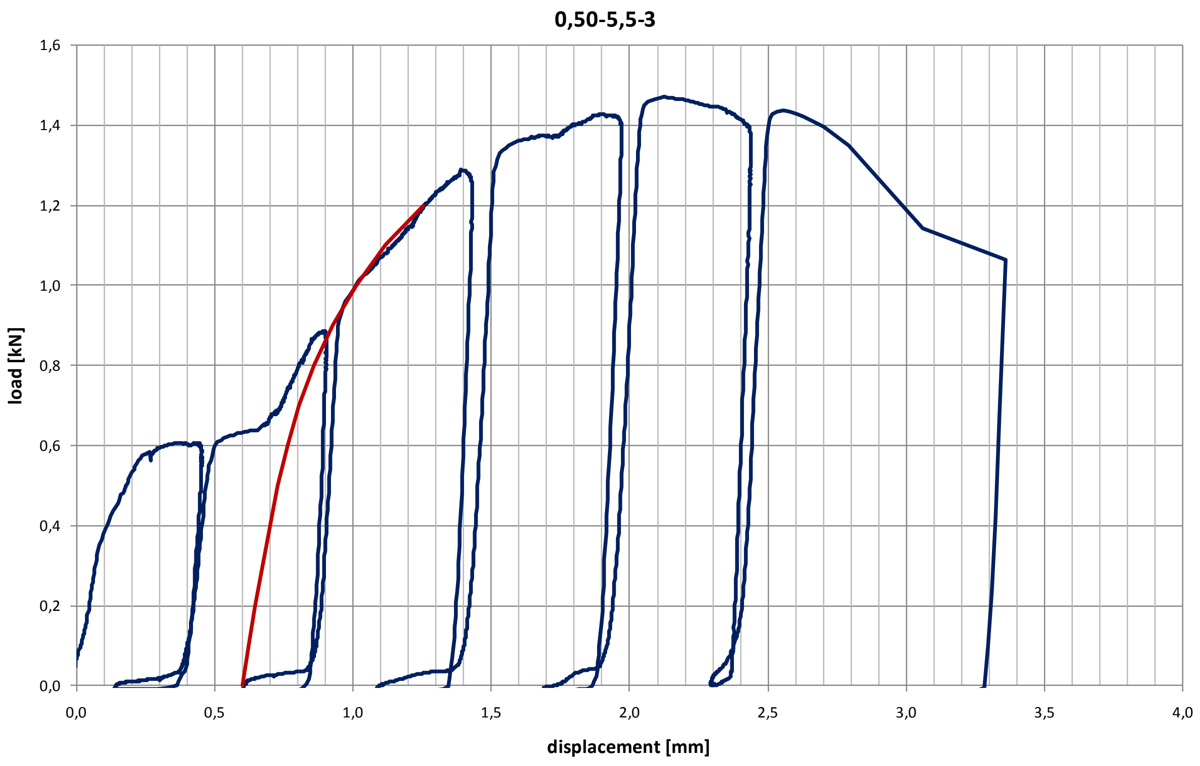
2,5
3,0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load [kN]
displacement [mm]
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1,4
1,2
1,0
0,8
0,6
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0,0
0,5
1,0
1,5
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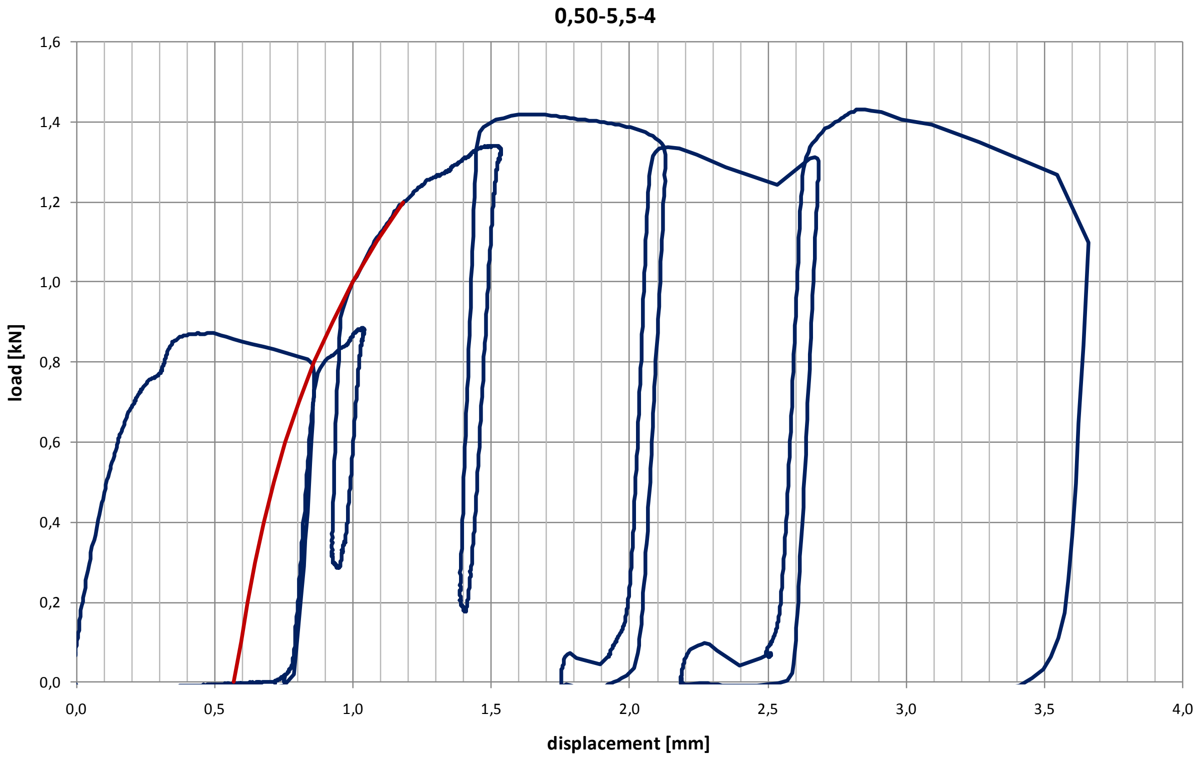
4,0


0,50-5,5-4
load [kN]
displacement [mm]
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1,4
1,2
1,0
0,8
0,6
0,4
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0,0
0,0
0,5
1,0
1,5
2,0
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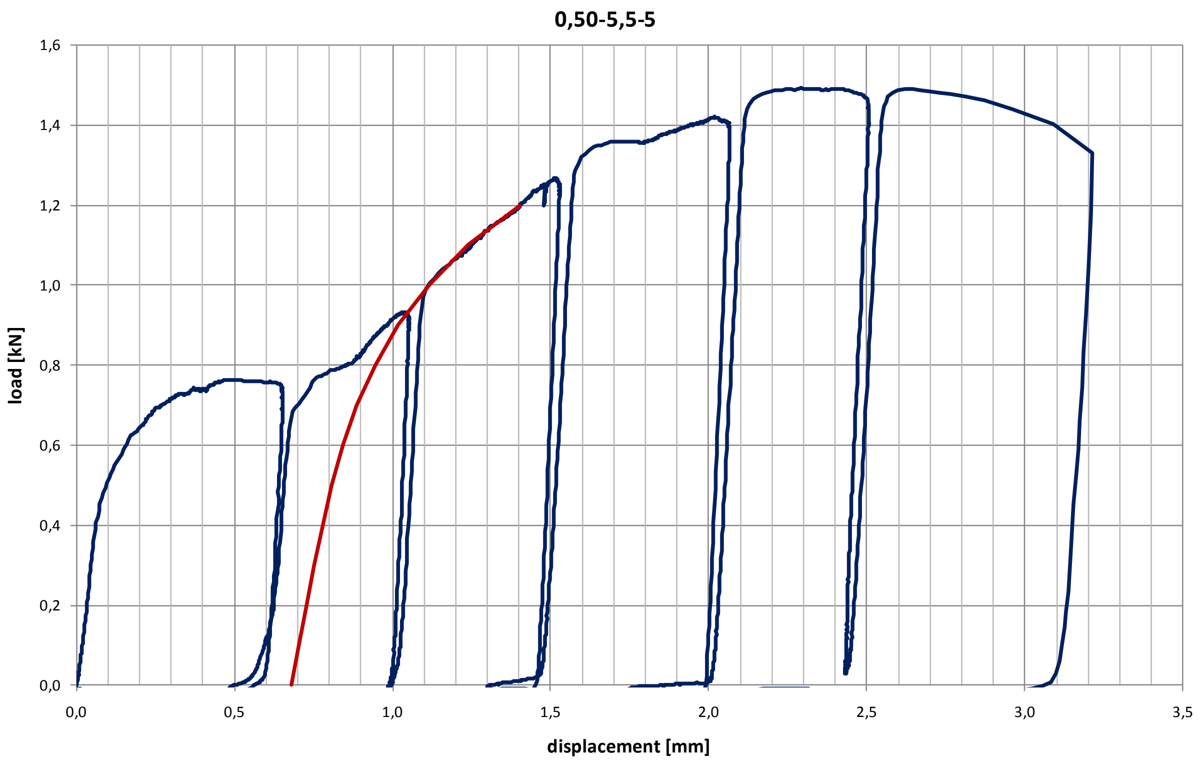
3,5
4,0


0,50-5,5-5
load [kN]
displacement [mm]
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1,4
1,2
1,0
0,8
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0,4
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0,0
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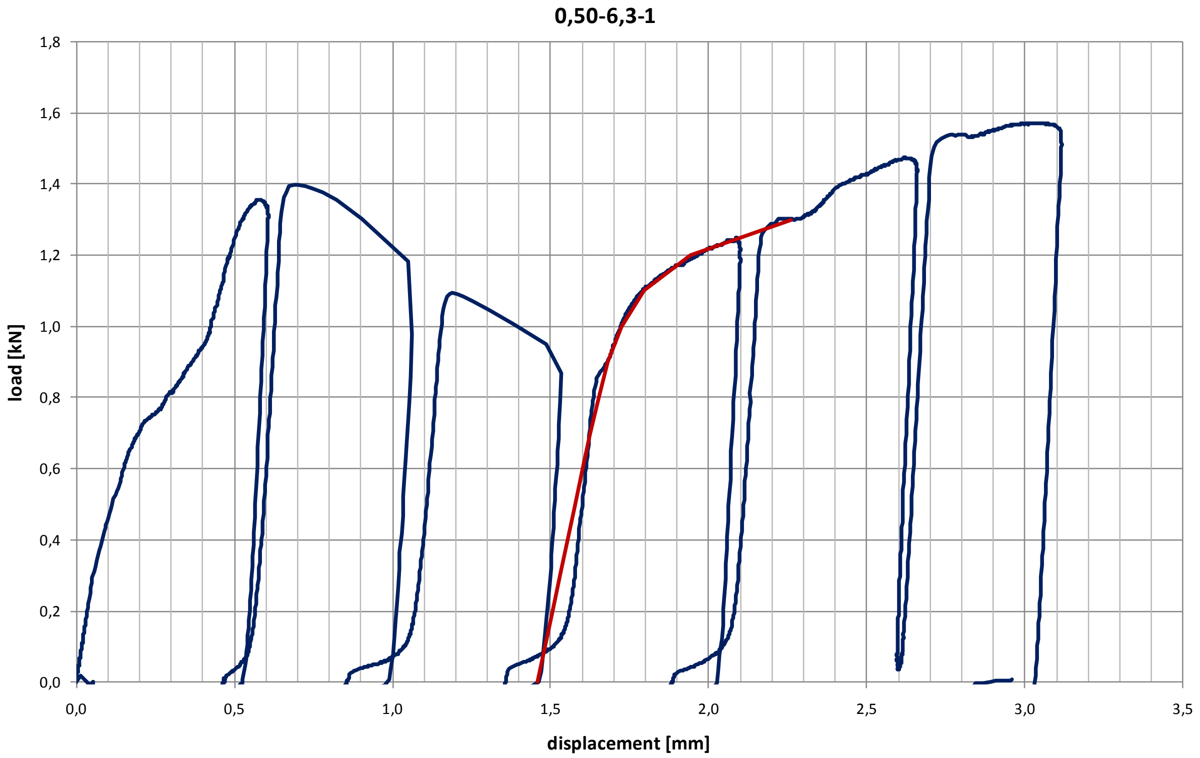
0,5
1,0
1,5
2,0
2,5
3,0
3,5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load [kN]
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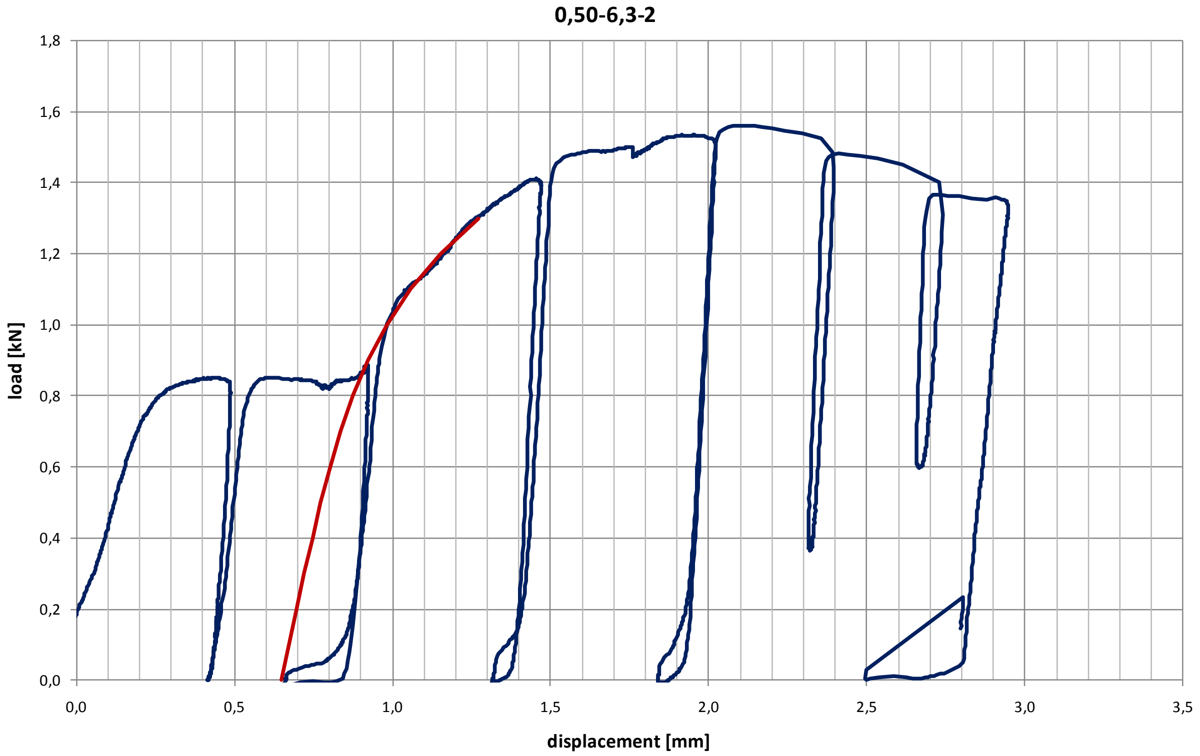
1,6
1,4
1,2
1,0
0,8
0,6
0,4
0,2
0,0
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5
displacement [mm]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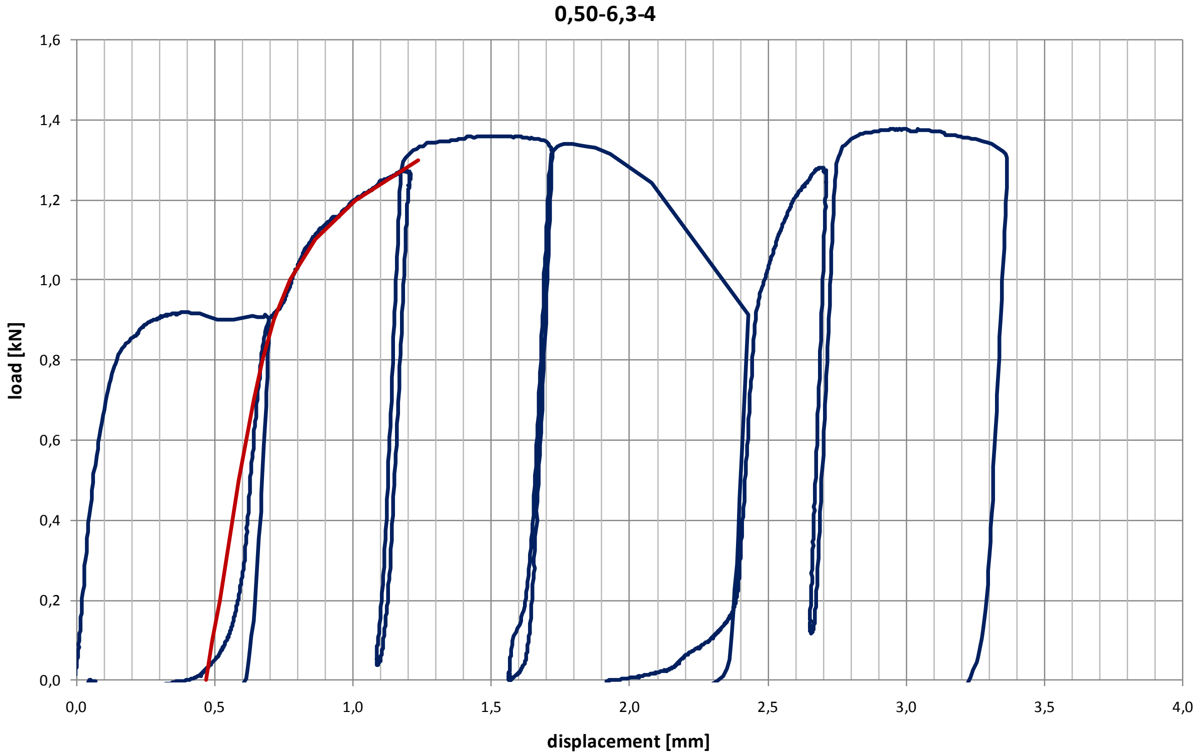
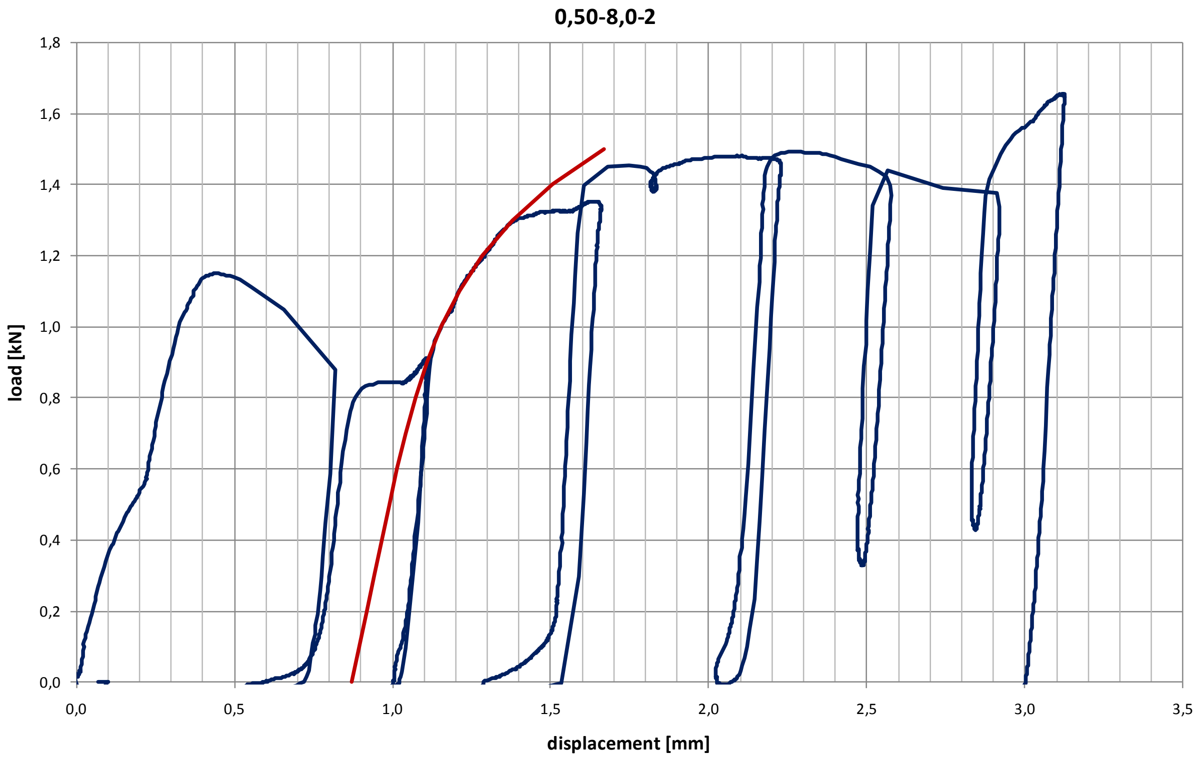
1,6
1,4
1,2
1,0
0,8
0,6
0,4
0,2
0,0
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5
displacement [mm]


0,50-6,3-4
load [kN]
displacement [mm]
1,6
1,4
1,2
1,0
0,8
0,6
0,4
0,2
0,0
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5
4,0


0,50-8,0-2
load [kN]
displacement [mm]
1,8
1,6
1,4
1,2
1,0
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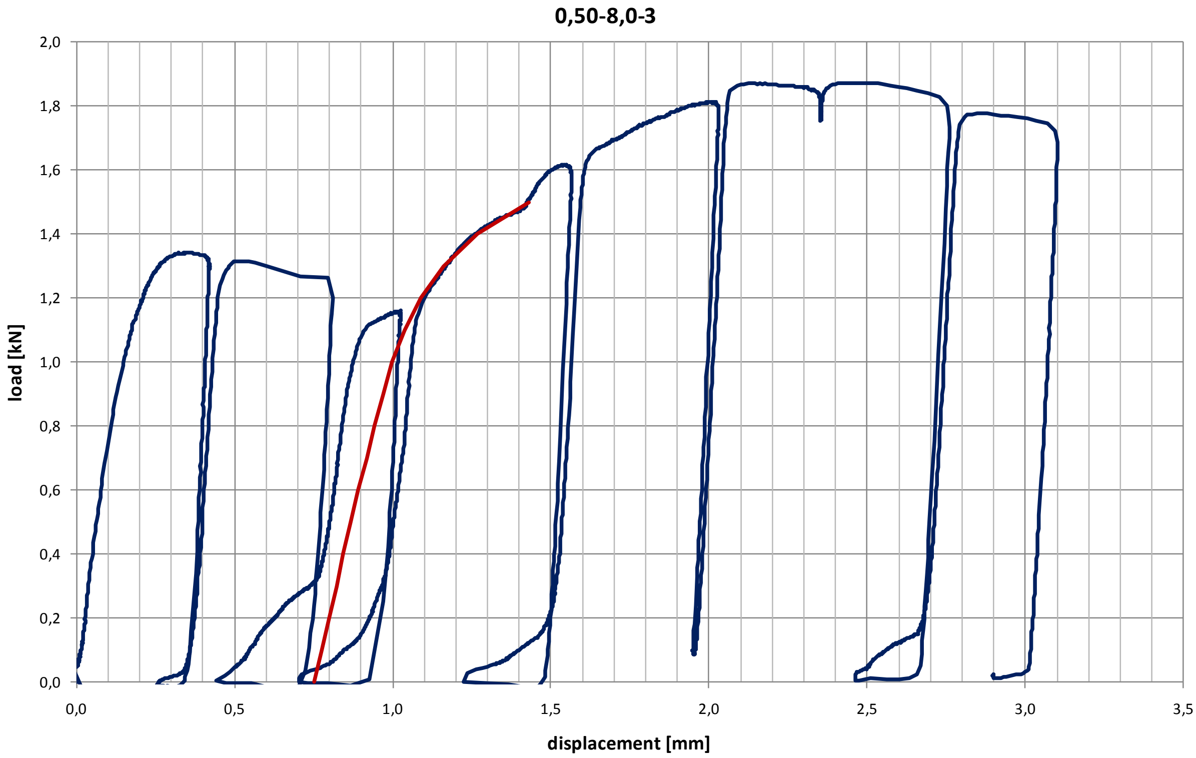
0,4
0,2
0,0
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5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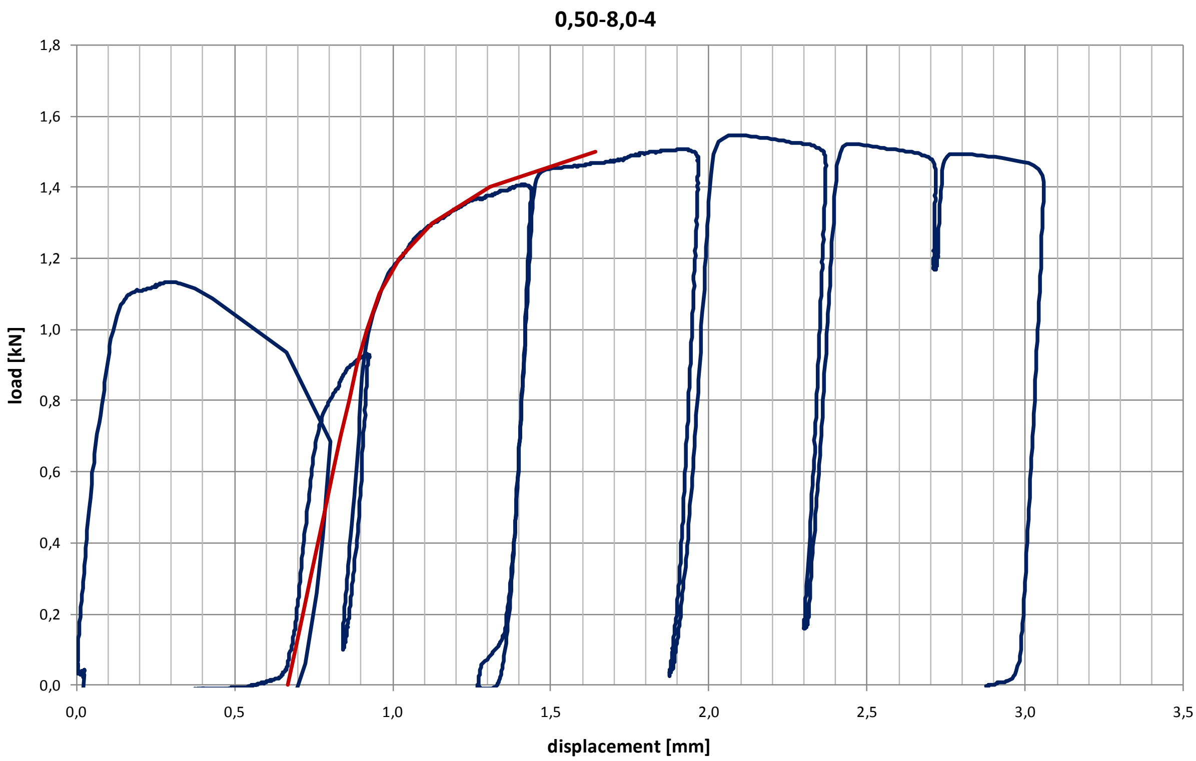
displacement [mm]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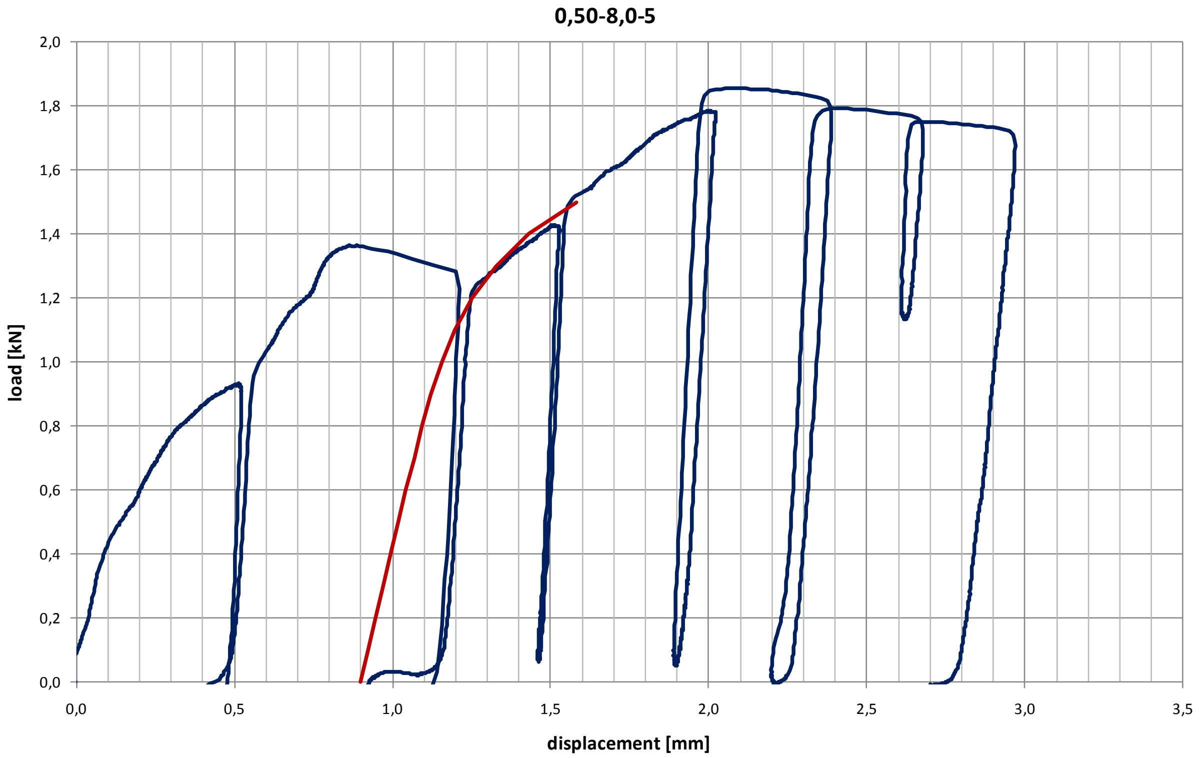
load [kN]
displacement [mm]


0,50-8,0-5
load [kN]
displacement [mm]
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1,8
1,6
1,4
1,2
1,0
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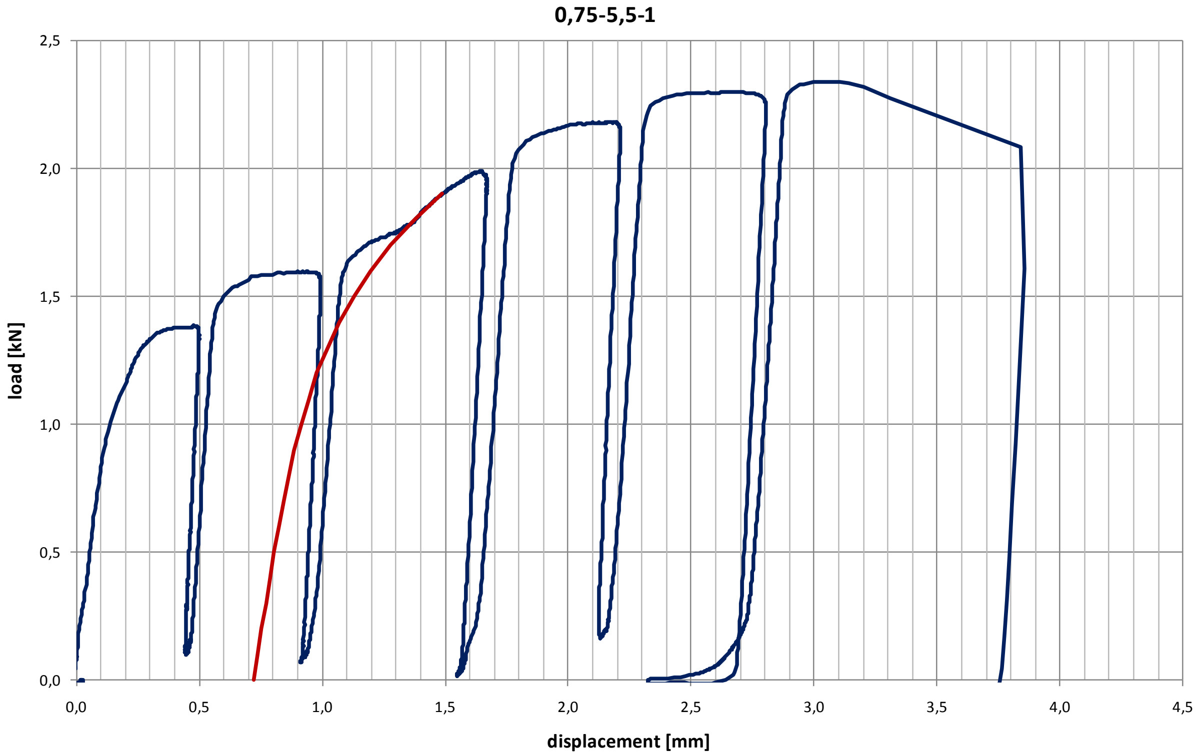
0,6
0,4
0,2
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5


0,75-5,5-1
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displacement [mm]
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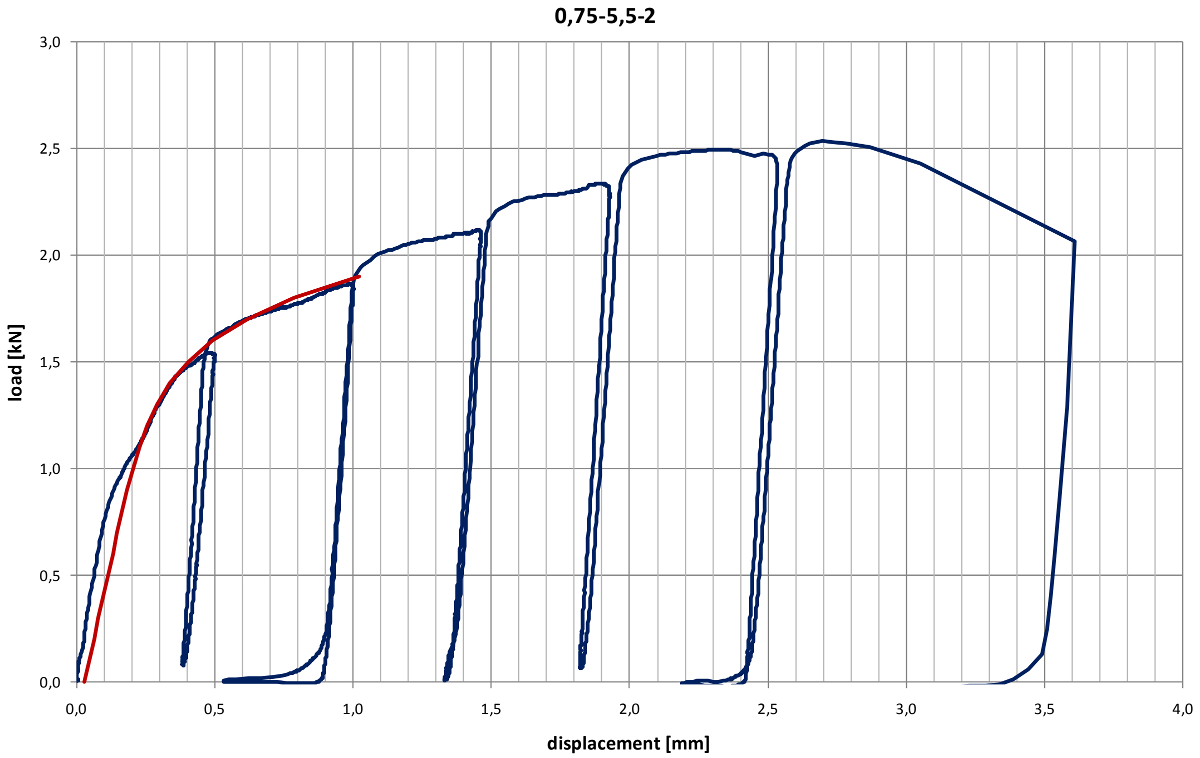
2,0
1,5
1,0
0,5
0,0
4,0
4,5


0,75-5,5-2
load [kN]
displacement [mm]
3,0
2,5
2,0
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0,0
0,5
1,0
1,5
2,0
2,5
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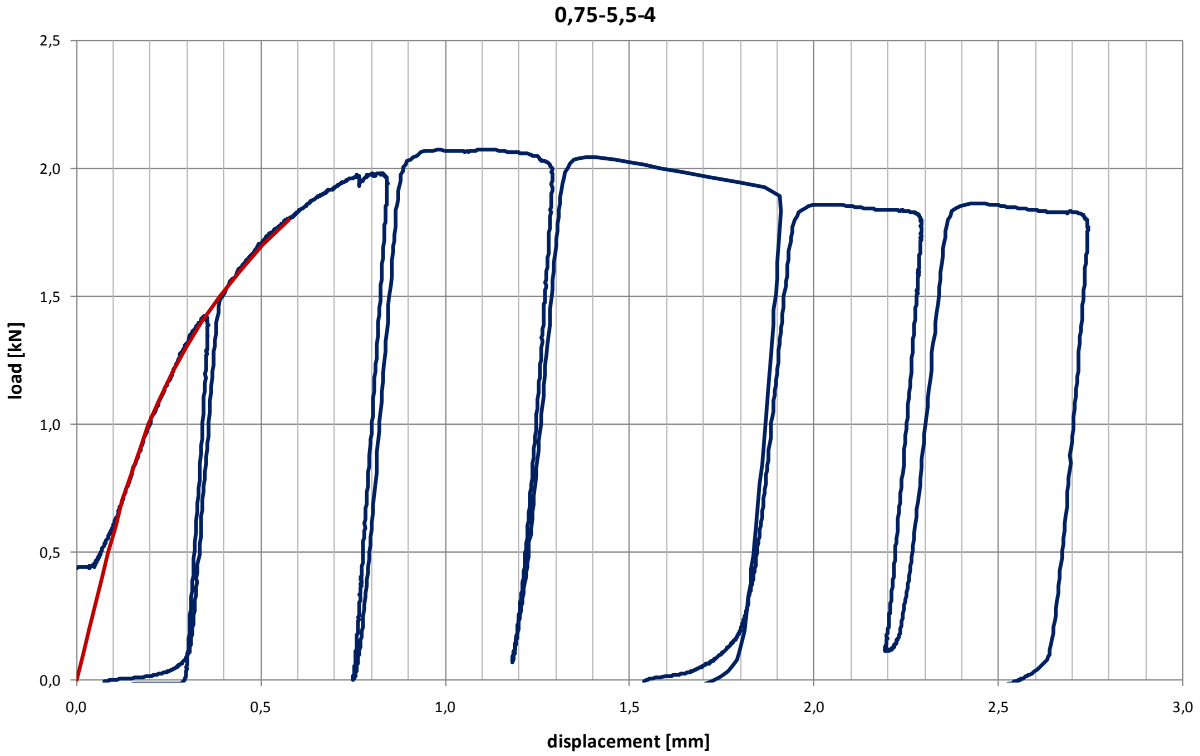
3,5
4,0


0,75-5,5-4
load [kN]
displacement [mm]
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1,5
1,0
0,5
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0,5
1,0
1,5
2,0
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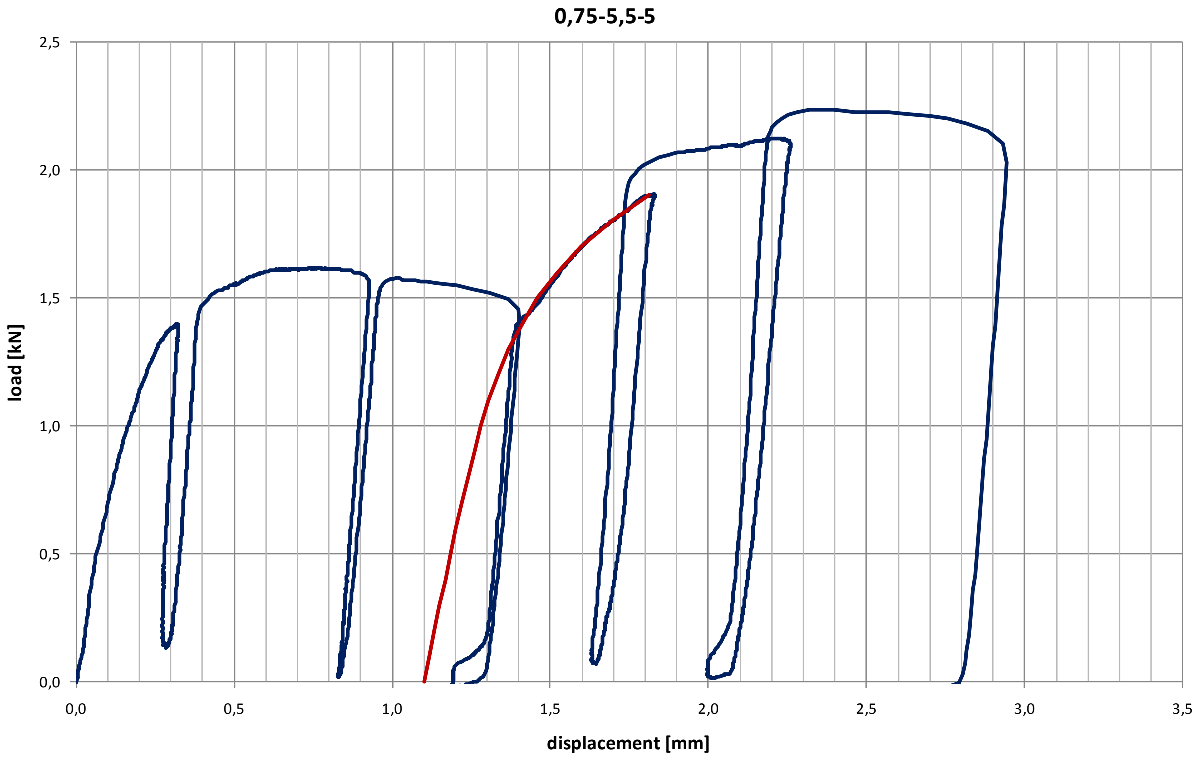
3,0


0,75-5,5-5
load [kN]
displacement [mm]
2,5
2,0
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1,0
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0,0
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1,0
1,5
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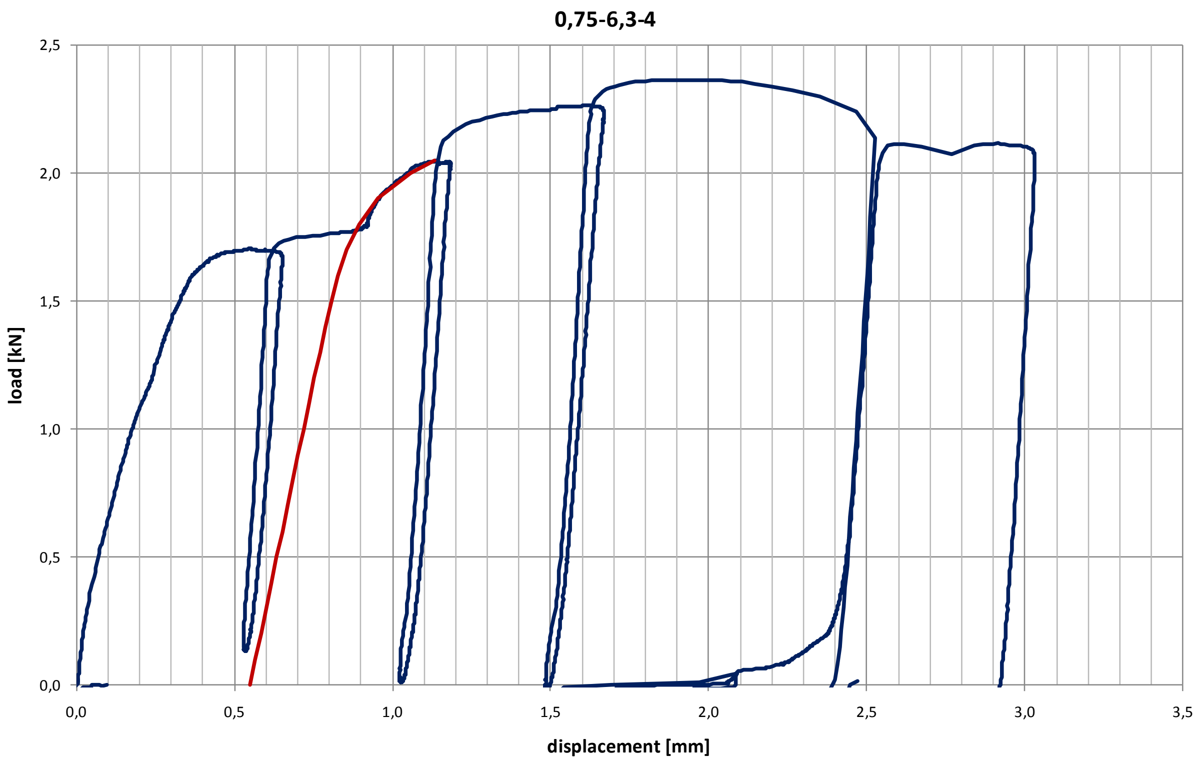
2,5
3,0
3,5


0,75-6,3-4
load [kN]
displacement [mm]
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2,0
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1,0
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0,0
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0,5
1,0
1,5
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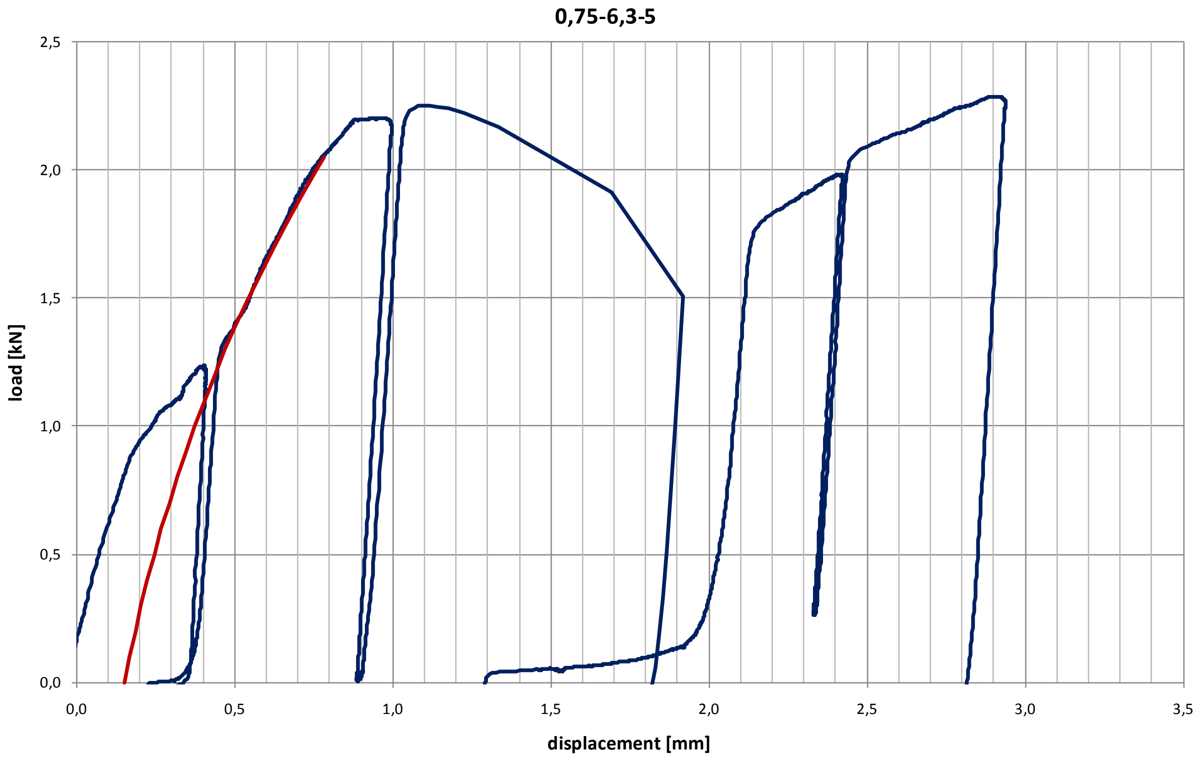
2,5
3,0
3,5


0,75-6,3-5
load [kN]
displacement [mm]
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1,0
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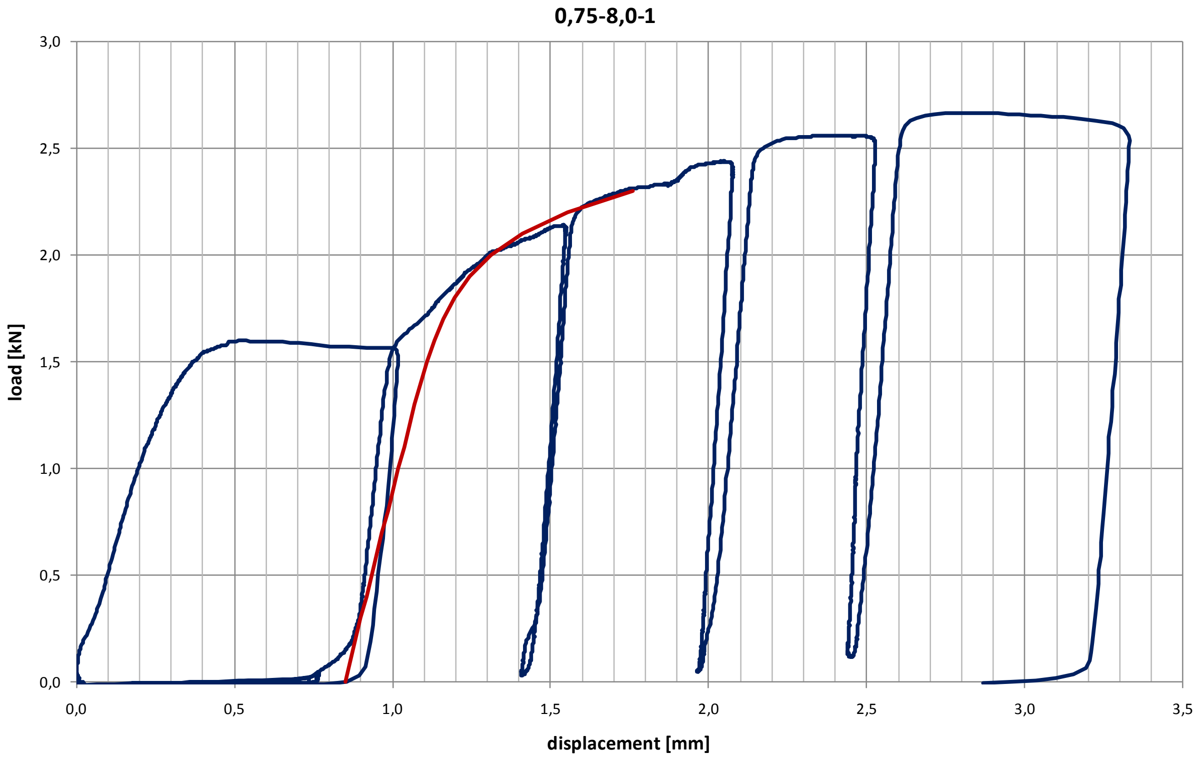
3,5


0,75-8,0-1
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displacement [mm]
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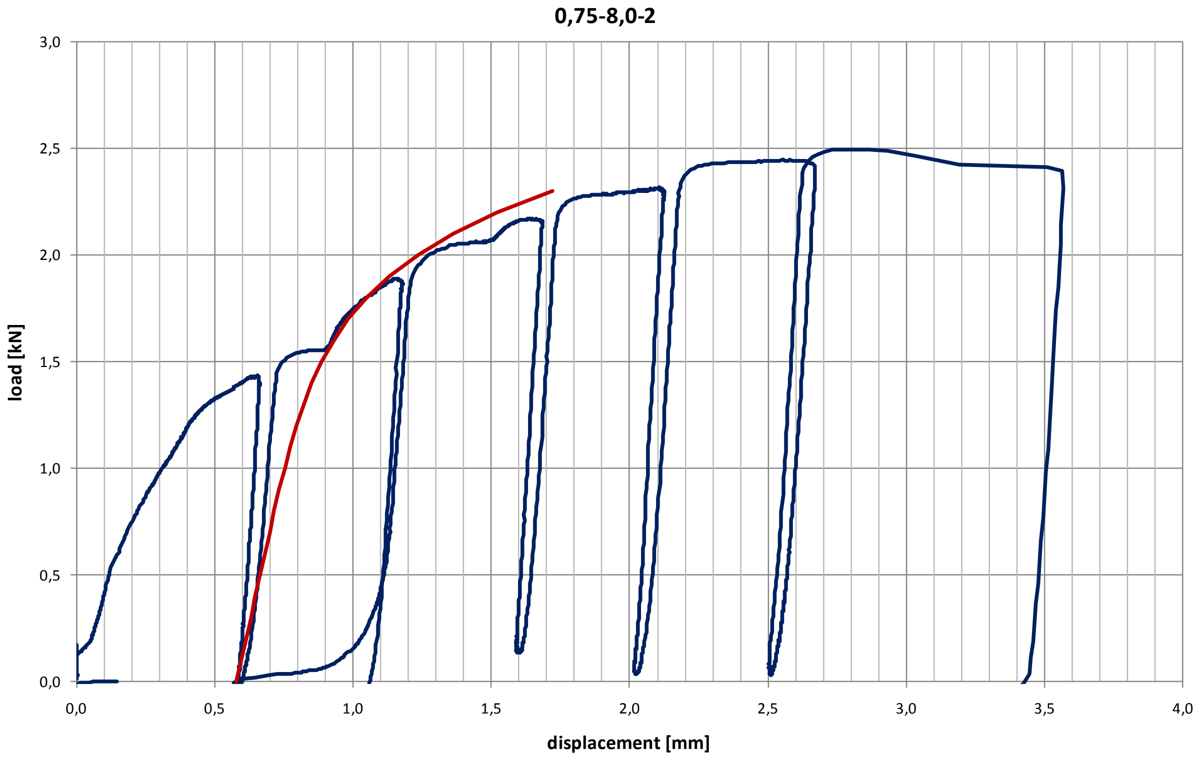
1,0
1,5
2,0
2,5
3,0
3,5


0,75-8,0-2
load [kN]
displacement [mm]
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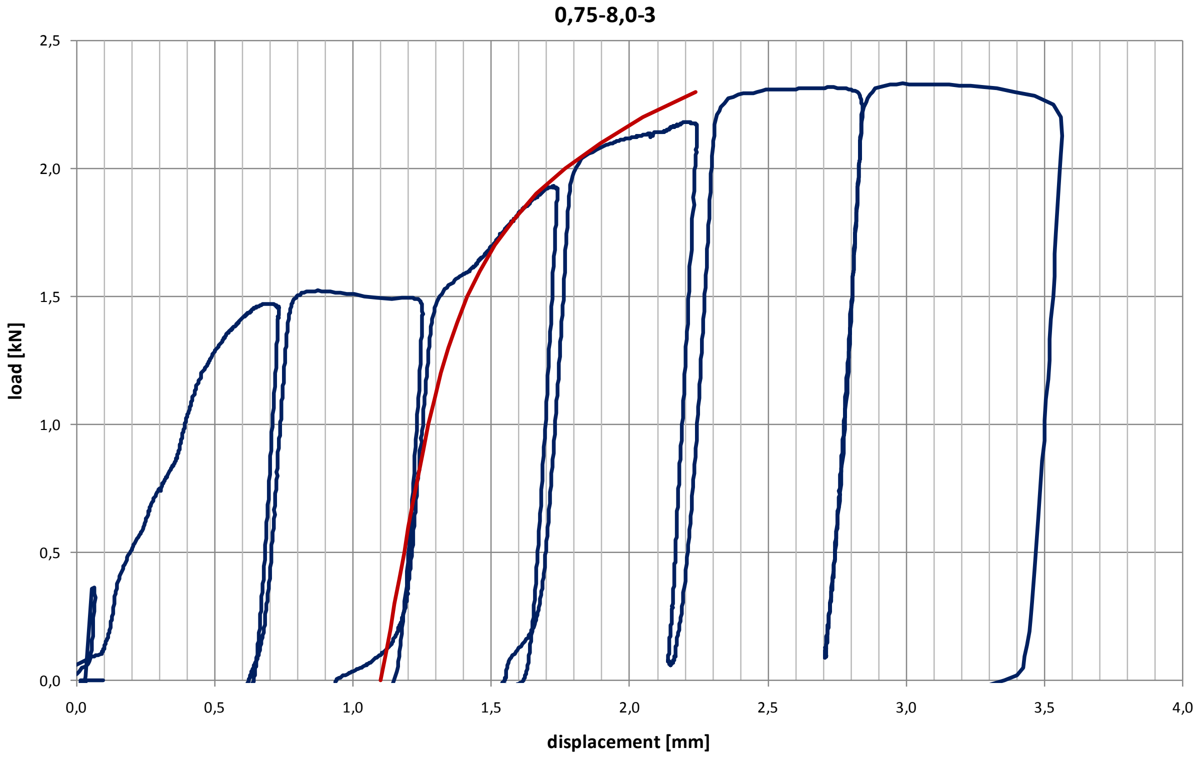
1,0
1,5
2,0
2,5
3,0
3,5
4,0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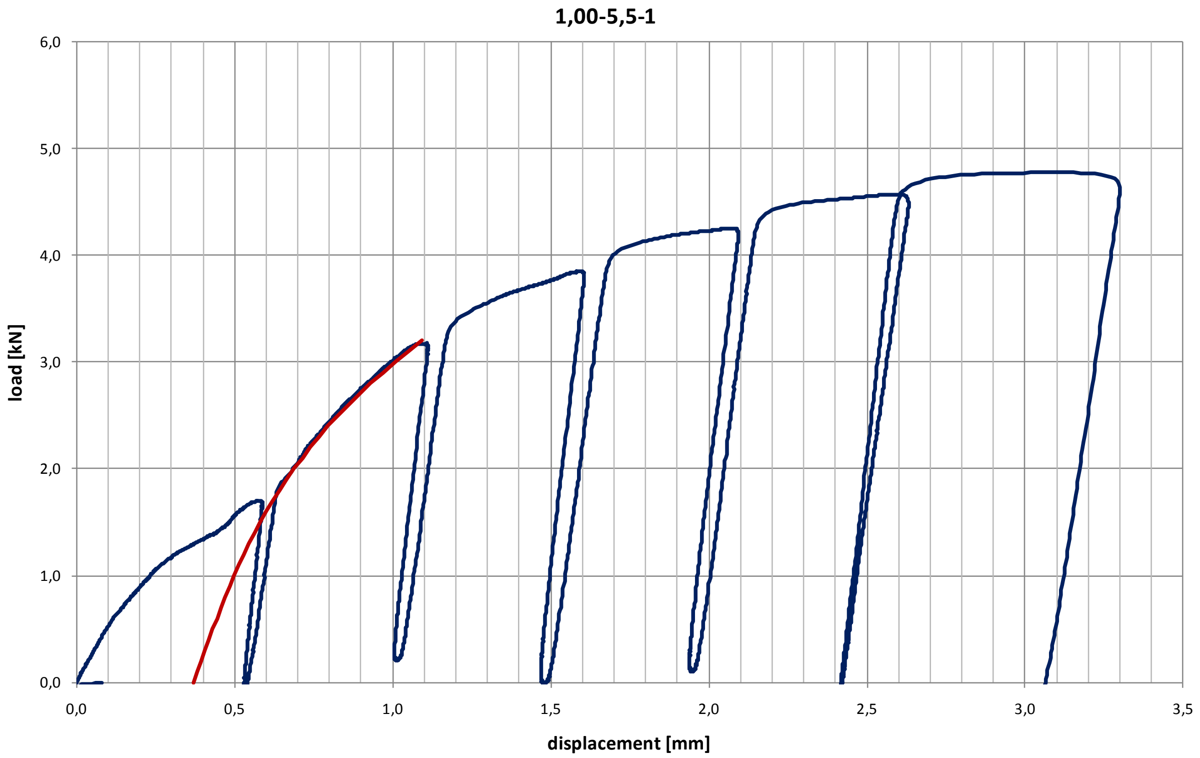
1,0
1,5
2,0
2,5
3,0
3,5
4,0


1,00-5,5-1
load [kN]
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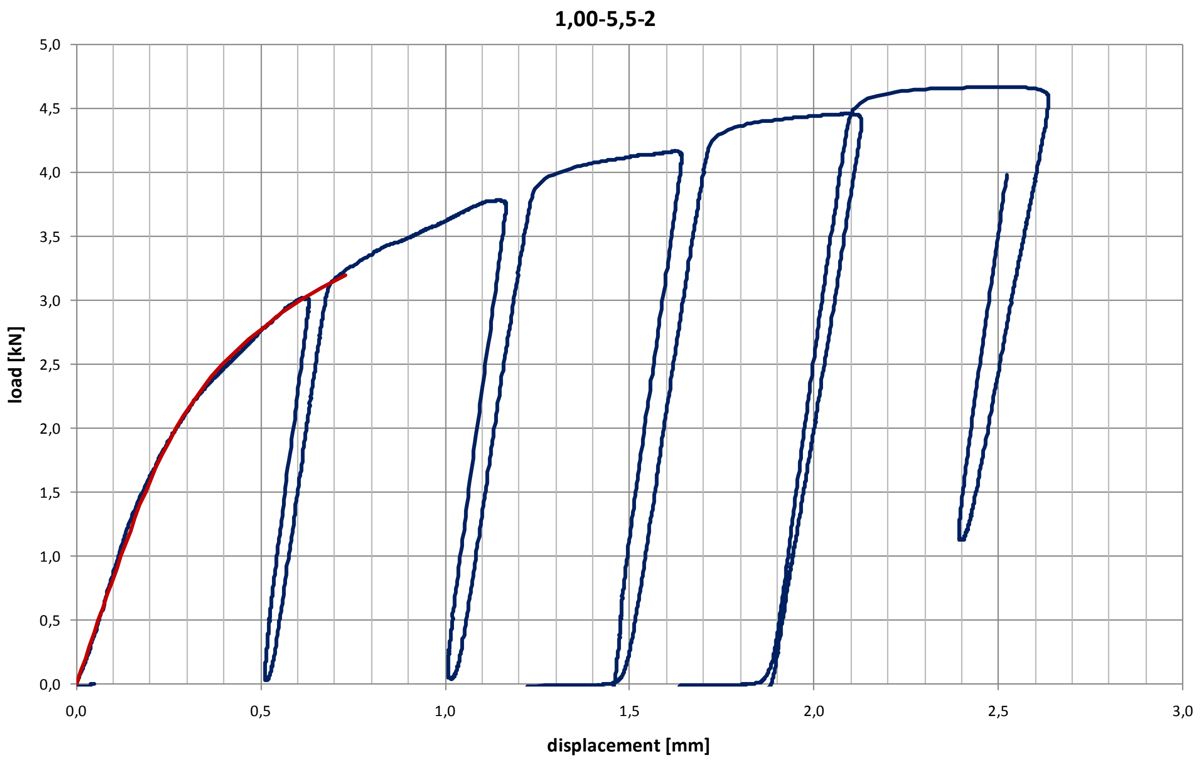
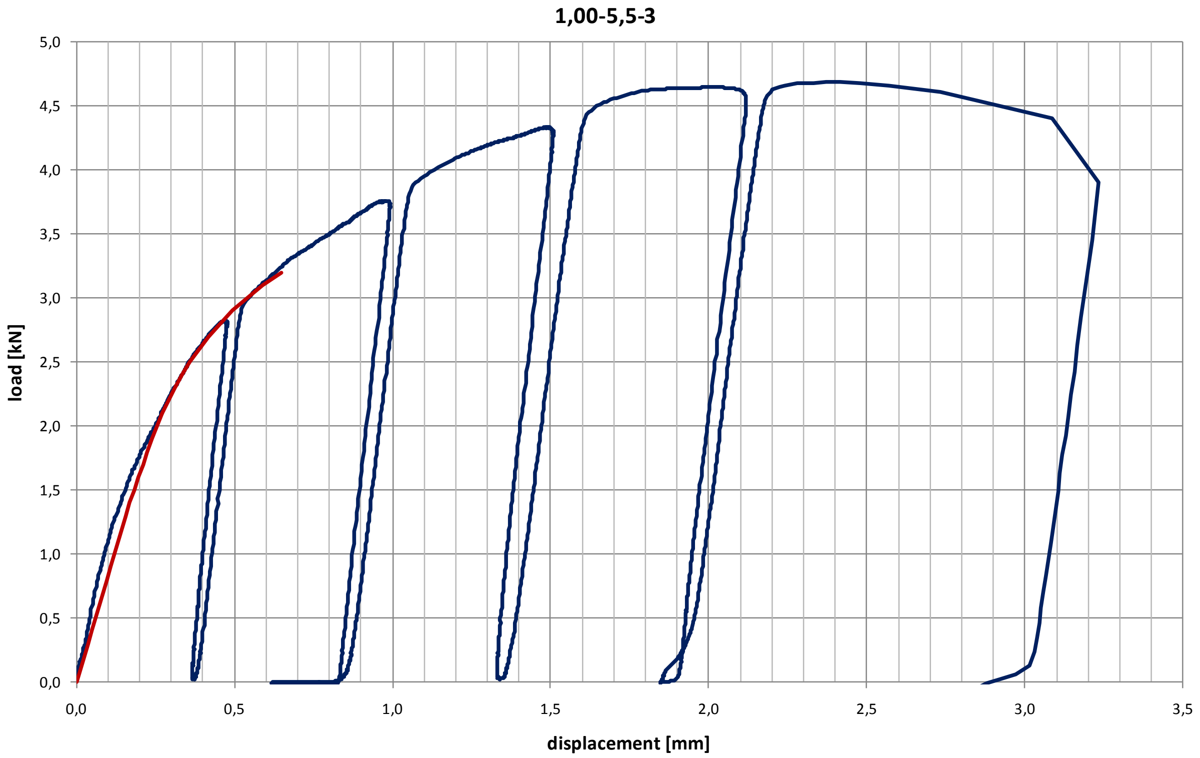
5,0
4,0
3,0
2,0
1,0
0,0
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5
displacement [mm]


1,00-5,5-2
load [kN]
5,0
4,5
4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
0,0
0,5
1,0
1,5
2,0
2,5
3,0
displacement [mm]


1,00-5,5-3
load [kN]
displacement [mm]
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4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
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0,5
1,0
1,5
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2,5
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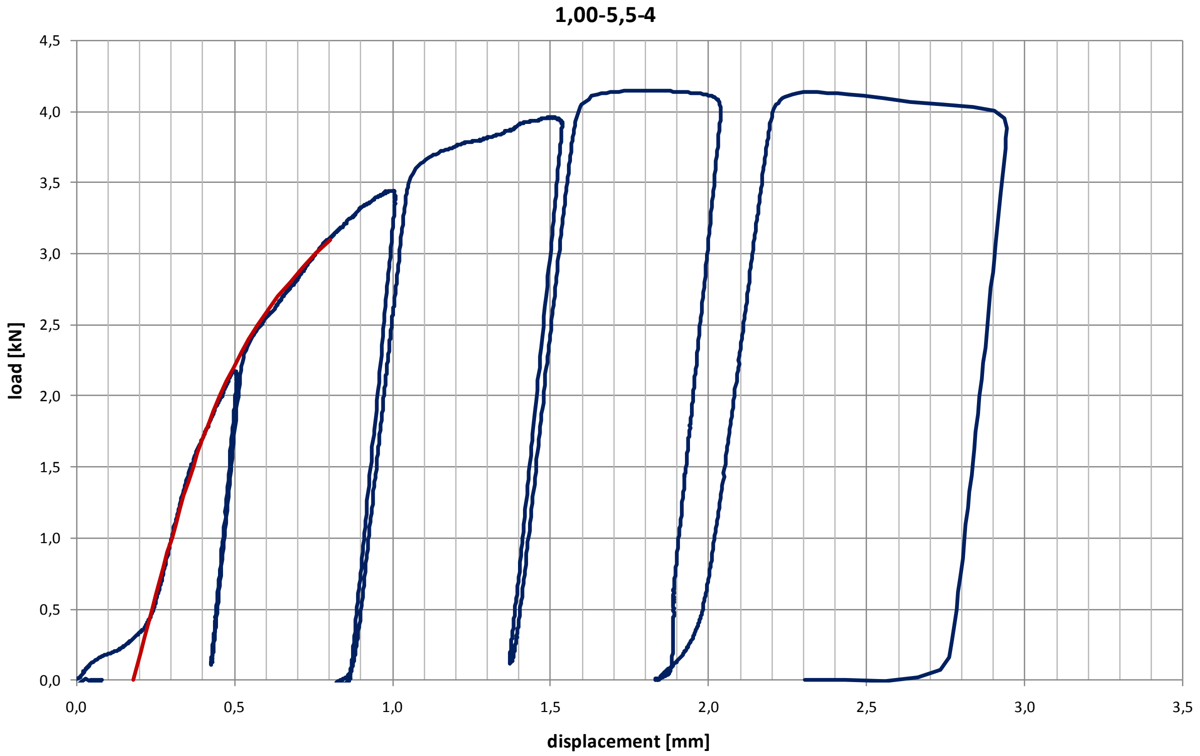
3,5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load [kN]
displacement [mm]
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3,5
3,0
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2,0
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0,5
1,0
1,5
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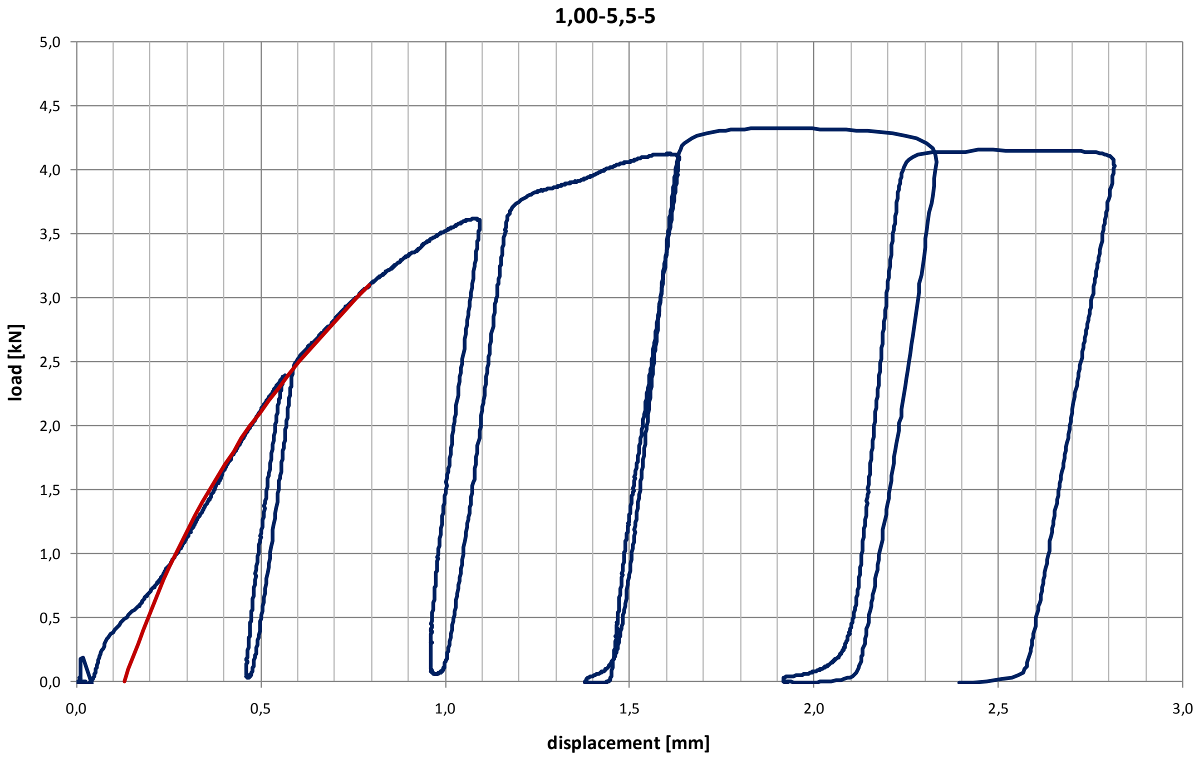
3,5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load [kN]
displacement [mm]
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4,0
3,5
3,0
2,5
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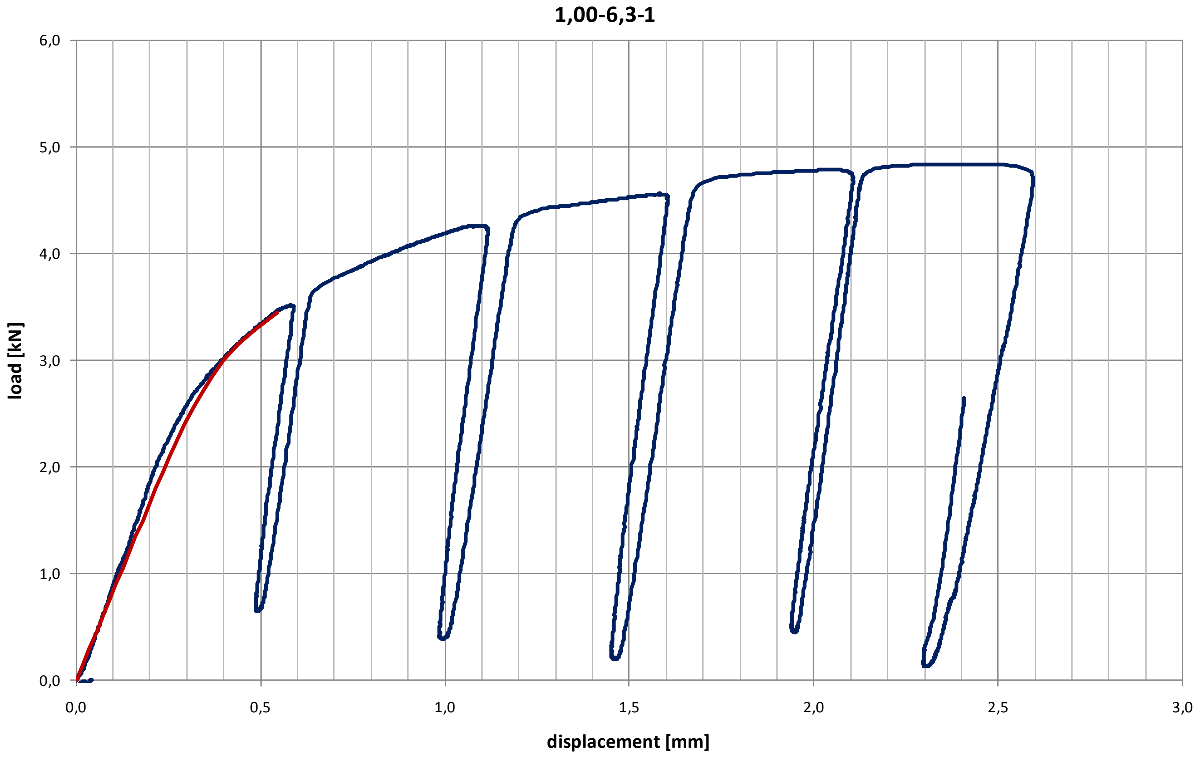
3,0


1,00-6,3-1
load [kN]
displacement [mm]
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3,0
2,0
1,0
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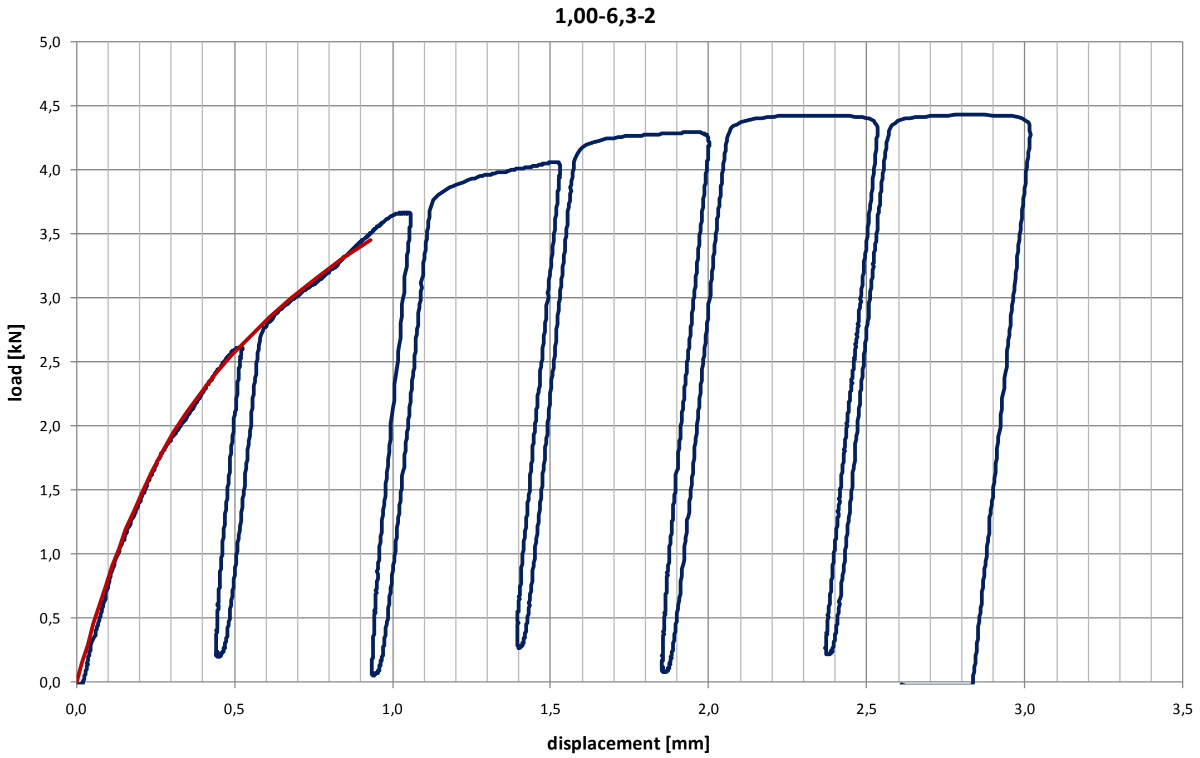
0,0
0,5
1,0
1,5
2,0
2,5
3,0


1,00-6,3-2
load [kN]
displacement [mm]
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4,5
4,0
3,5
3,0
2,5
2,0
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1,0
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0,0
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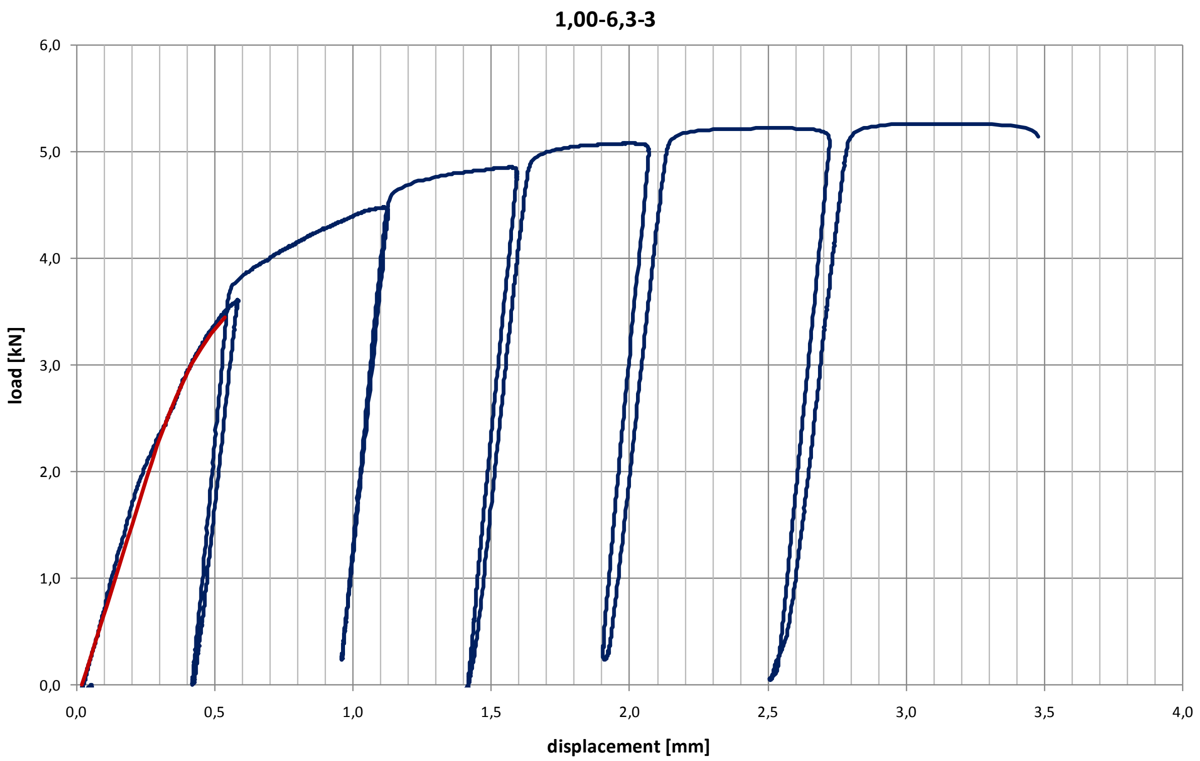
3,0
3,5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load [kN]
displacement [mm]
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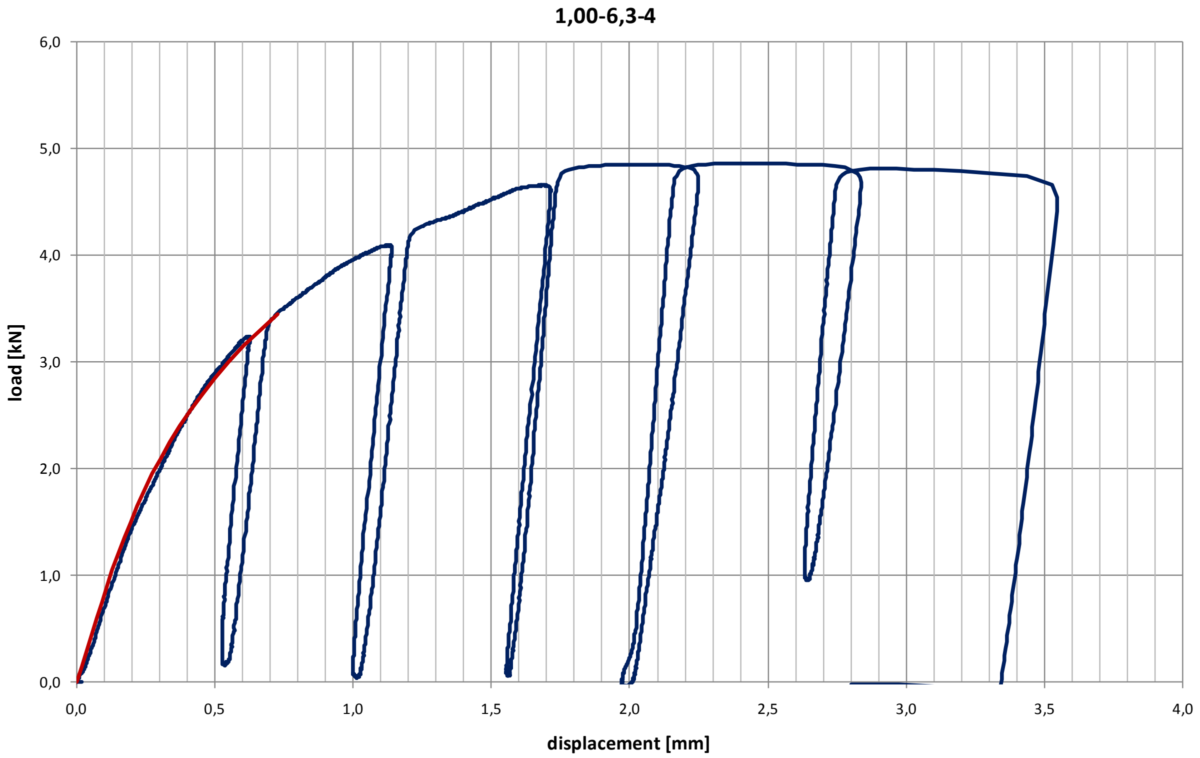
4,0
3,0
2,0
1,0
0,0
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5
4,0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load [kN]
displacement [mm]
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0,0
0,5
1,0
1,5
2,0
2,5
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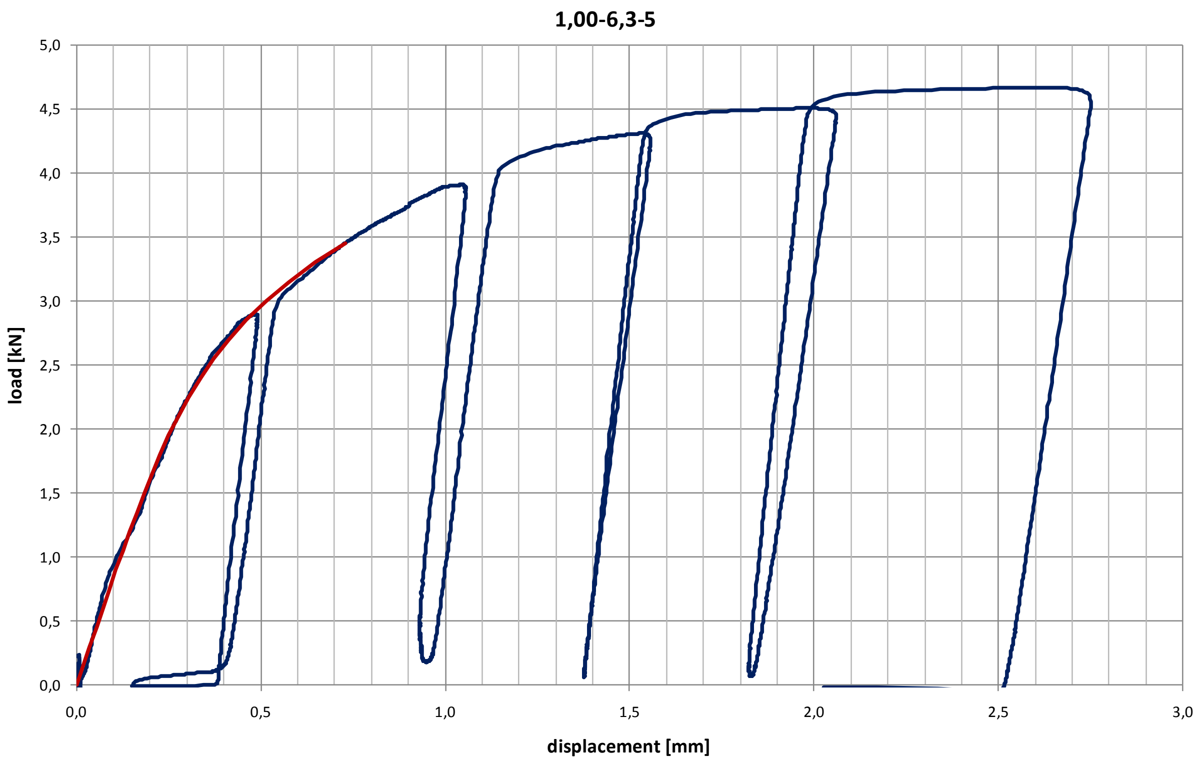
3,5
4,0


1,00-6,3-5
load [kN]
displacement [mm]
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4,5
4,0
3,5
3,0
2,5
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1,0
0,5
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0,0
0,5
1,0
1,5
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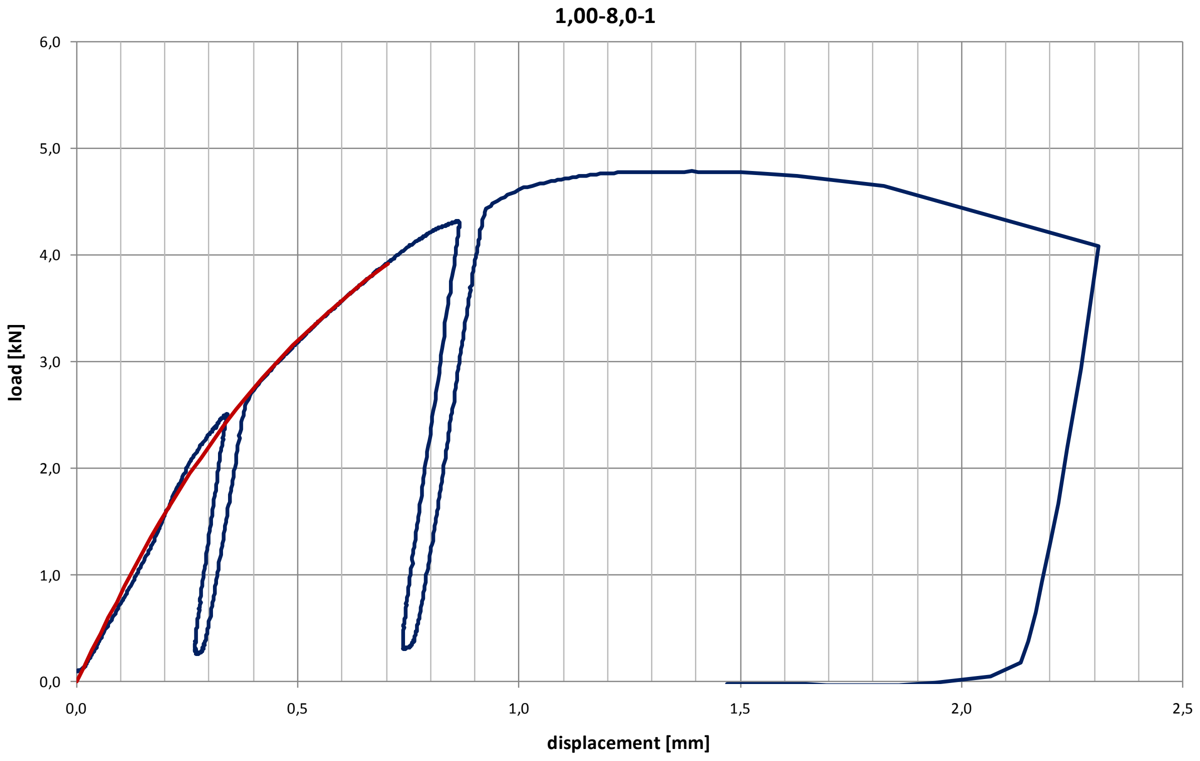
2,5
3,0


1,00-8,0-1
load [kN]
displacement [mm]
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0,5
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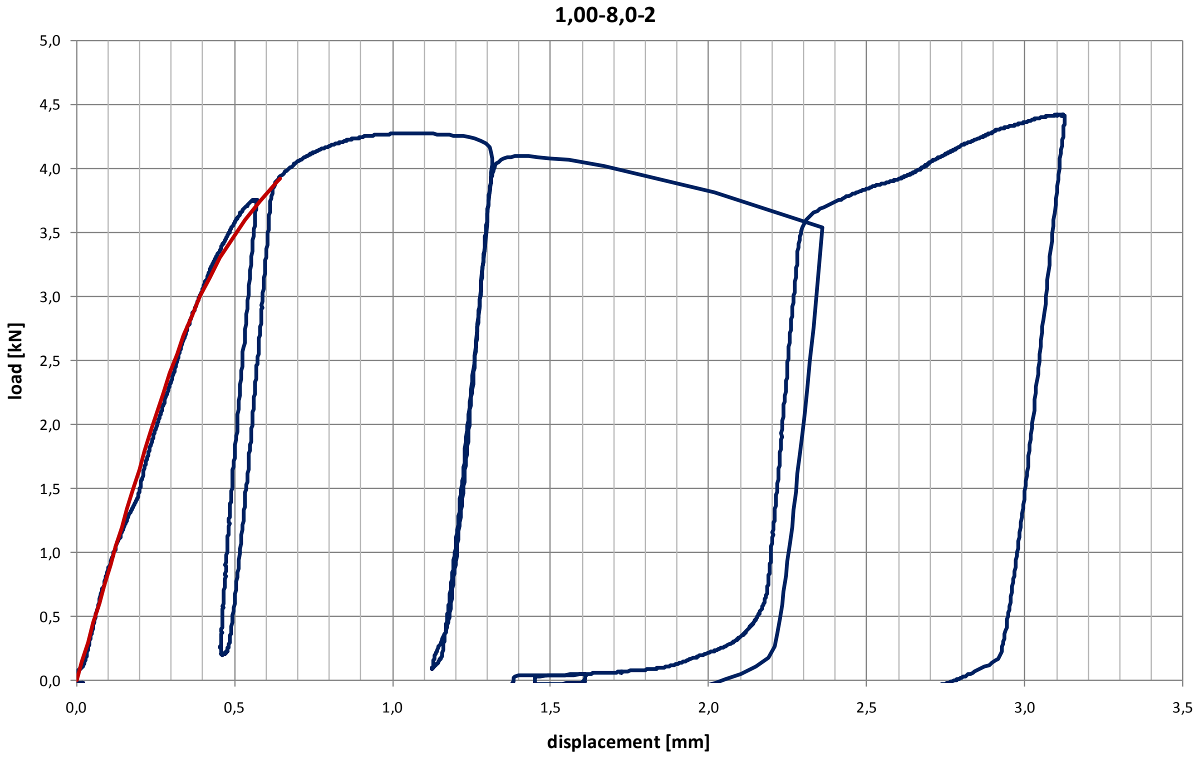
1,5
2,0
2,5


1,00-8,0-2
load [kN]
displacement [mm]
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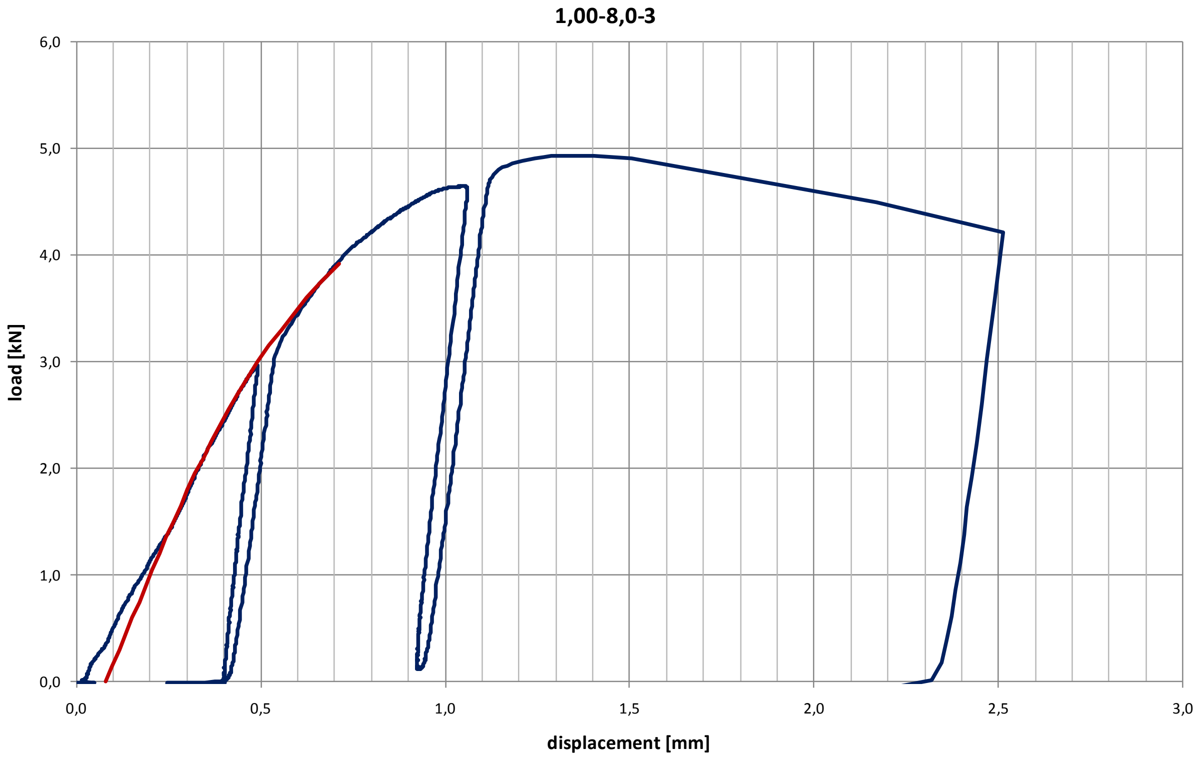
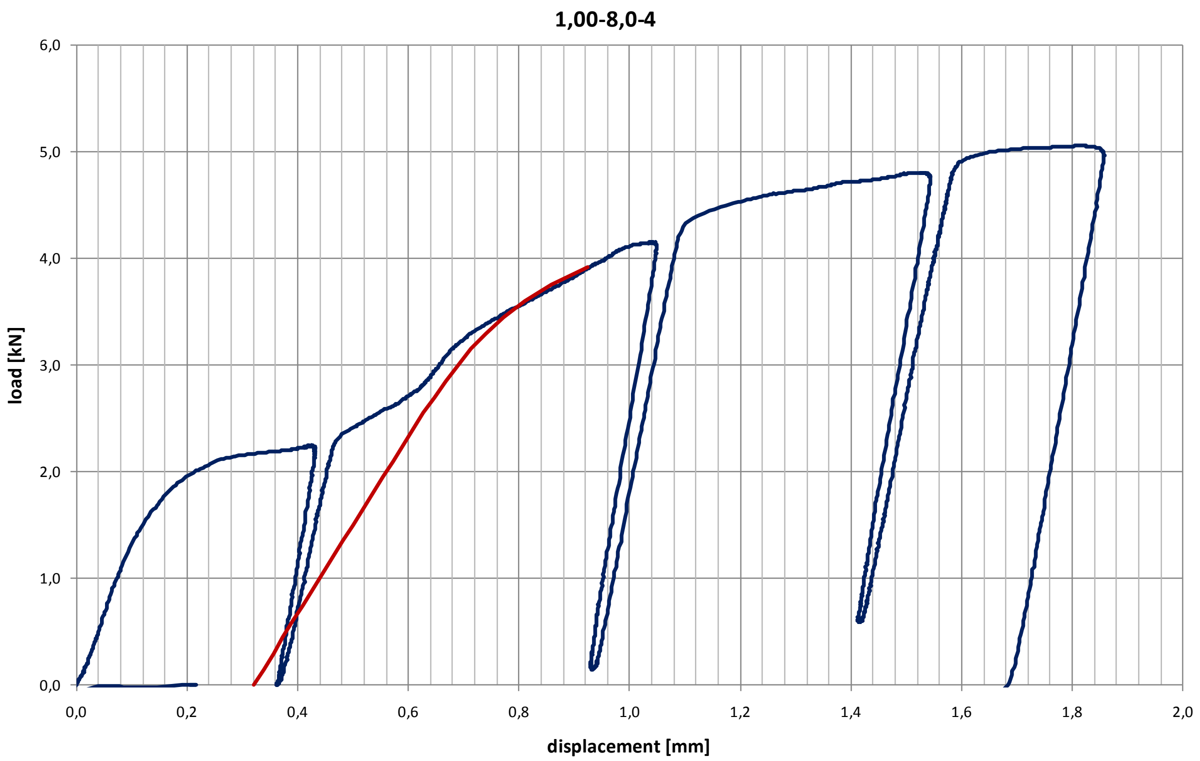
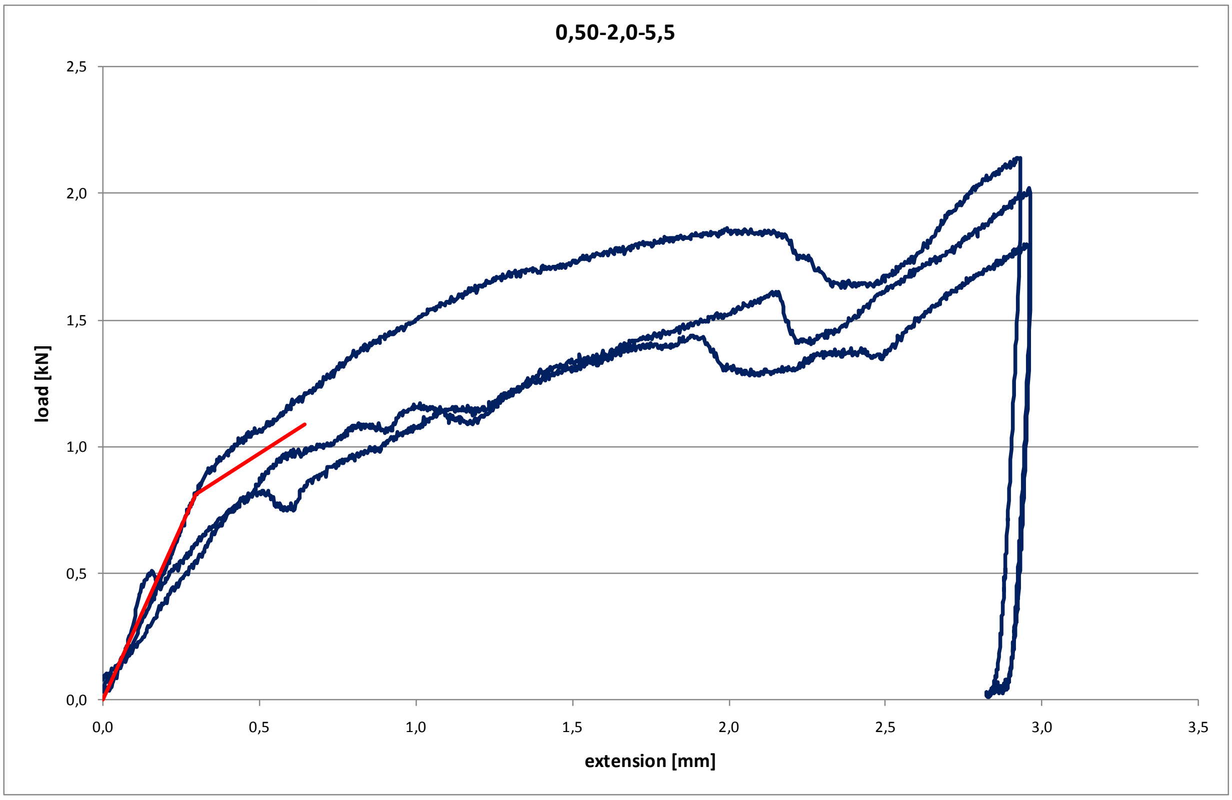
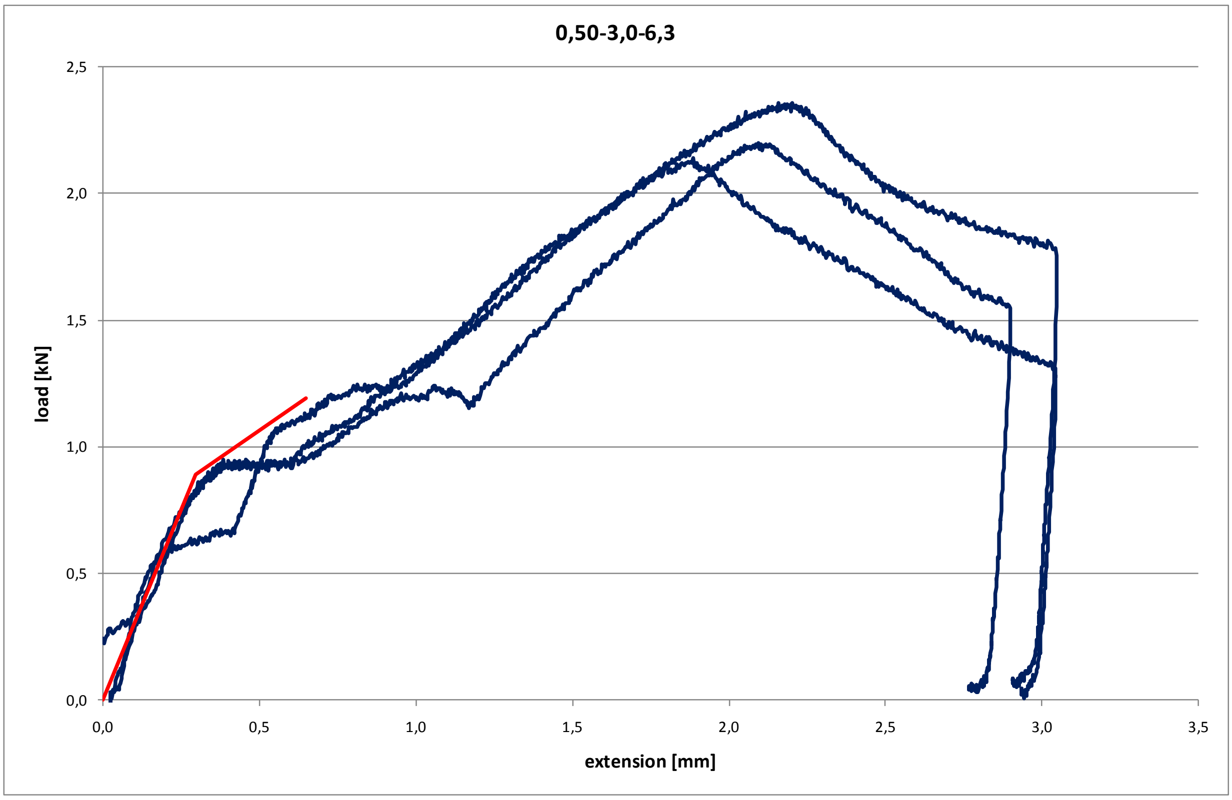
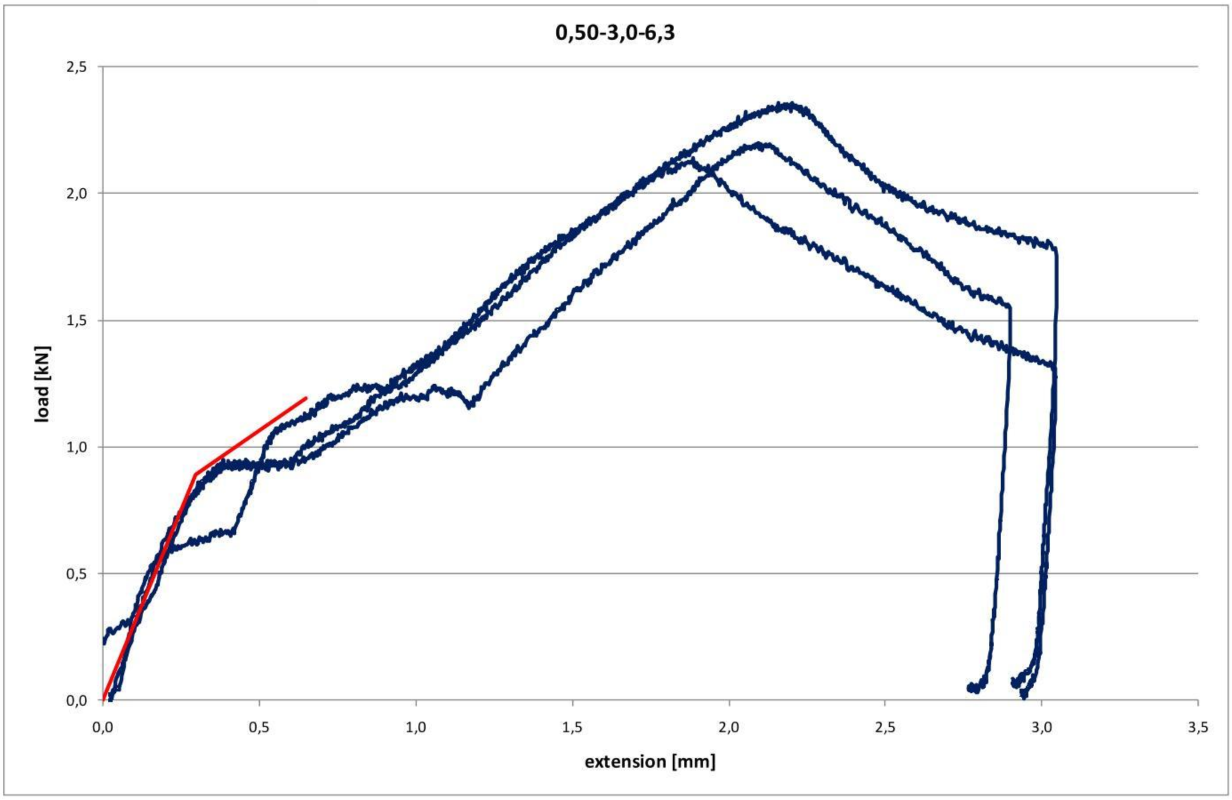
4,5
4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5

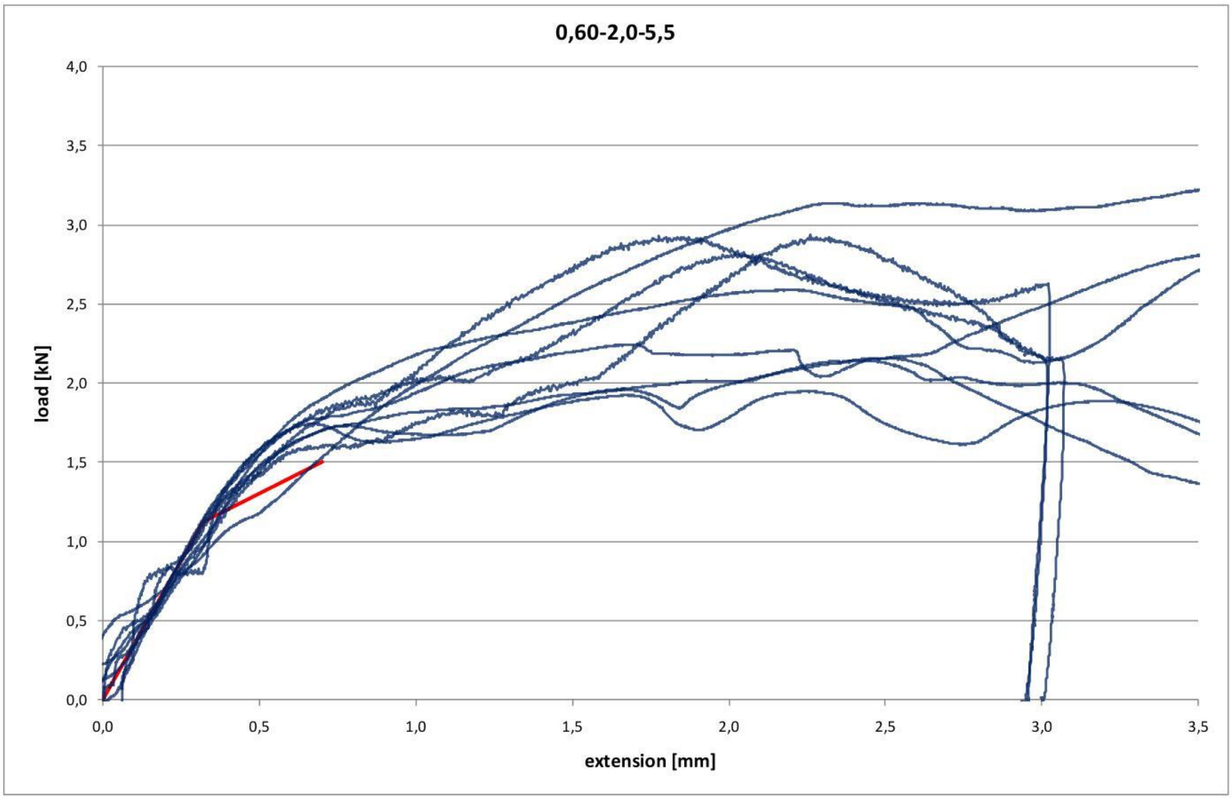

1,00-8,0-3
load [kN]
displacement [mm]
6,0
5,0
4,0
3,0
2,0
1,0
0,0
0,0
0,5
1,0
1,5
2,0
2,5
3,0

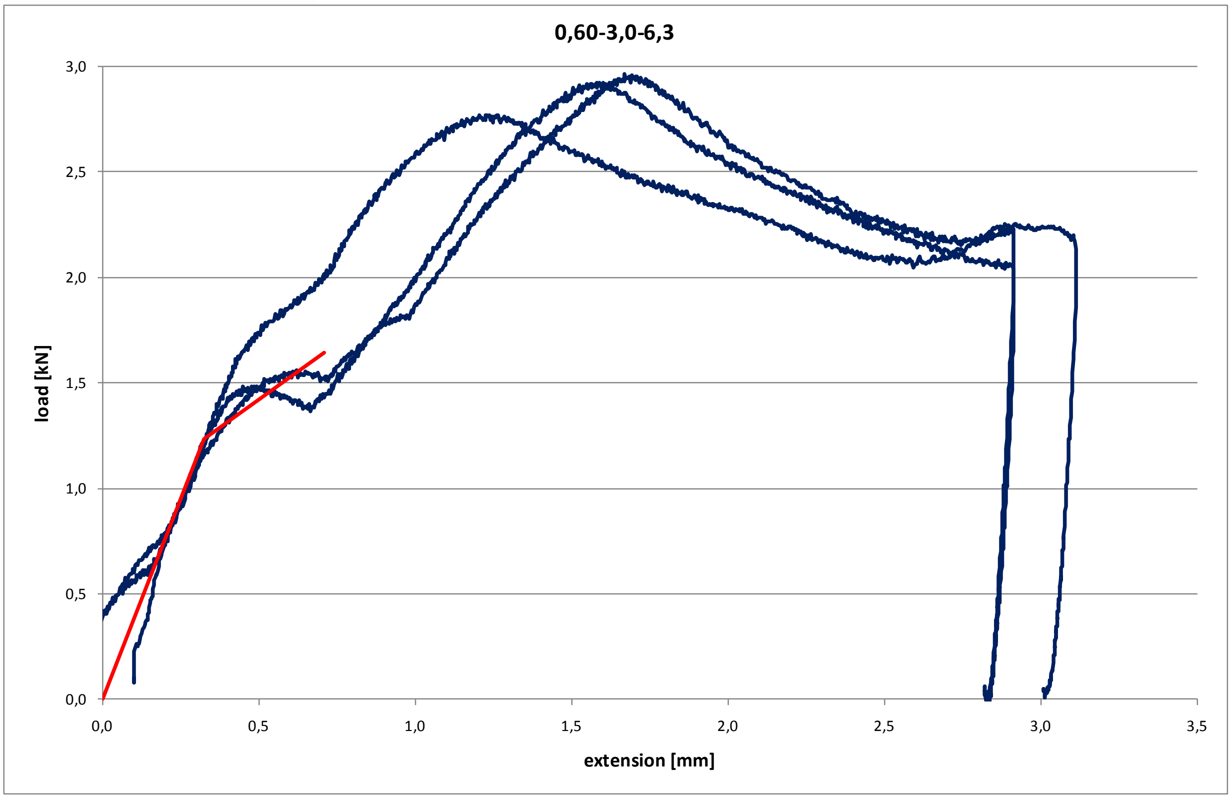

1,00-8,0-4
load [kN]
displacement [mm]
6,0
5,0
4,0
3,0
2,0
1,0
0,0
0,0
0,2
0,4
0,6
0,8
1,0
1,2
1,4
1,6
1,8
2,0

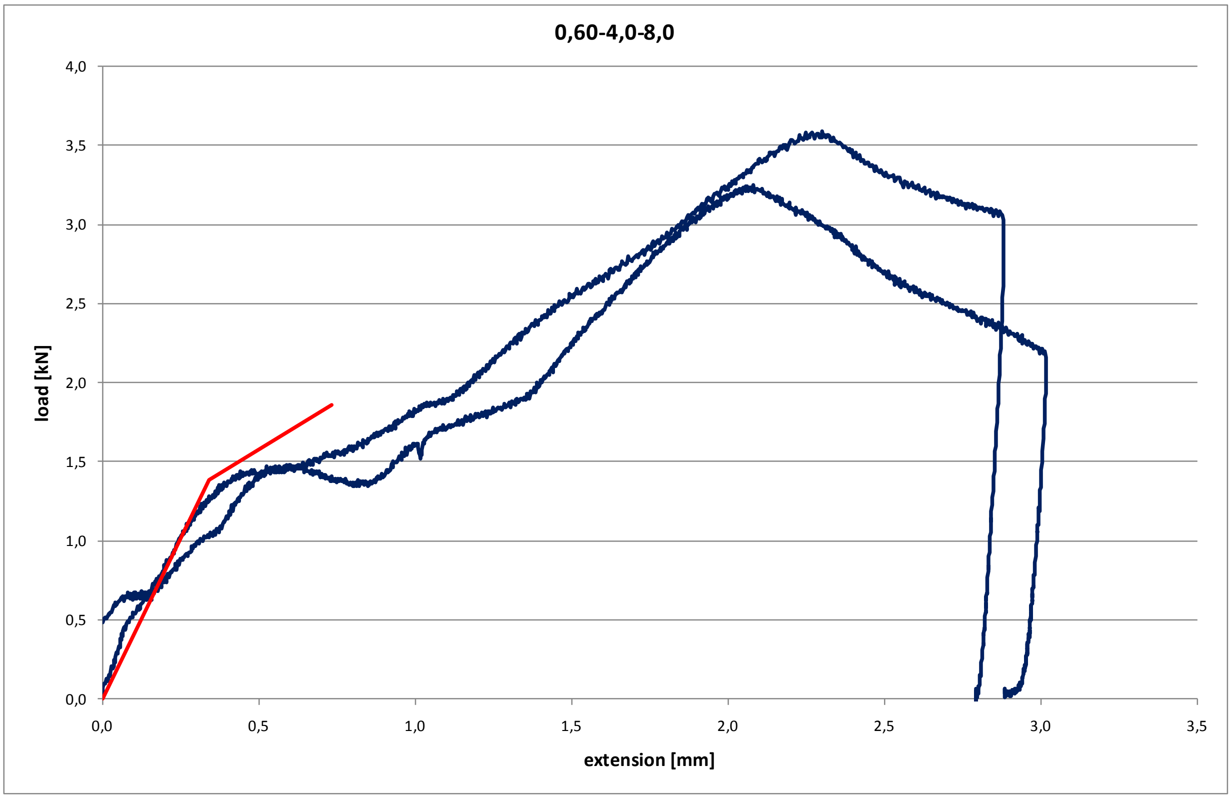

0,50-2,0-5,5
load [kN]
0,0
0,5
1,0
1,5
2,0
2,5
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5
extension [mm]

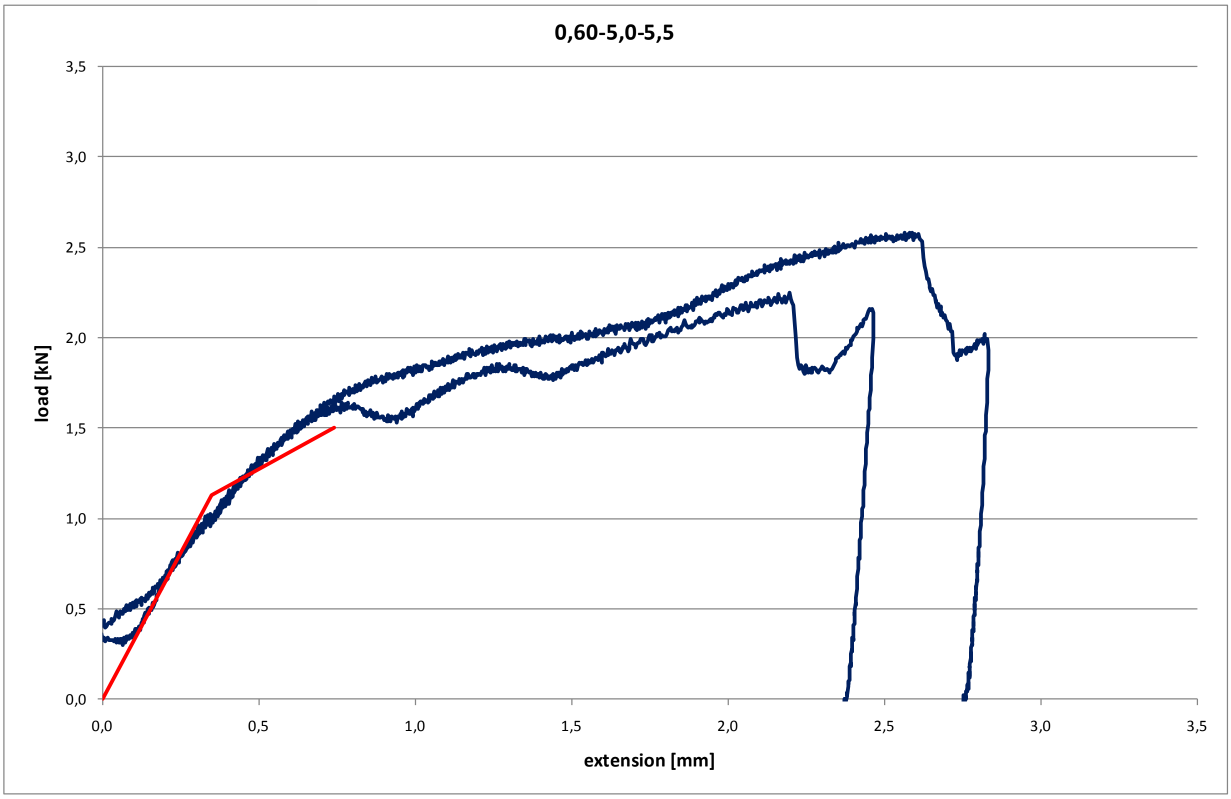

0,50-3,0-6,3
load [kN]
0,0
0,5
1,0
1,5
2,0
2,5
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5
extension [mm]

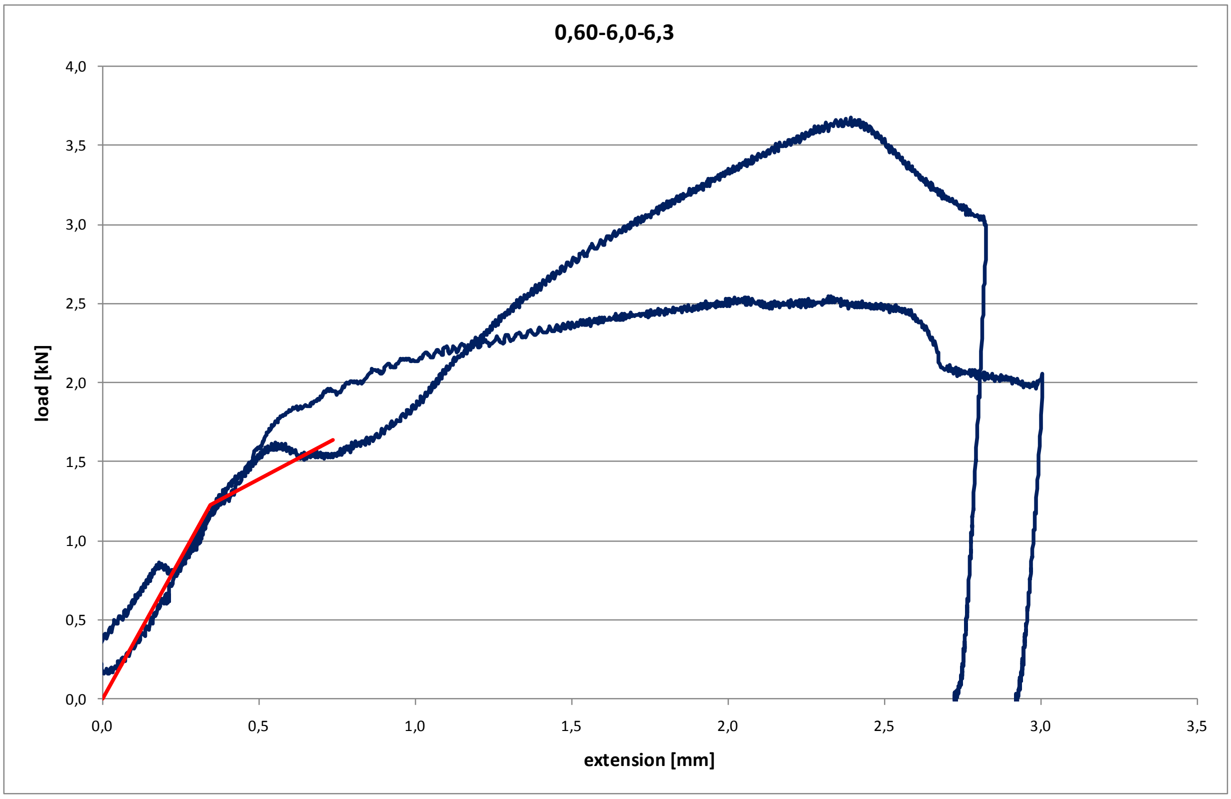

0,50-3,0-6,3
load [kN]
extension [mm]
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5

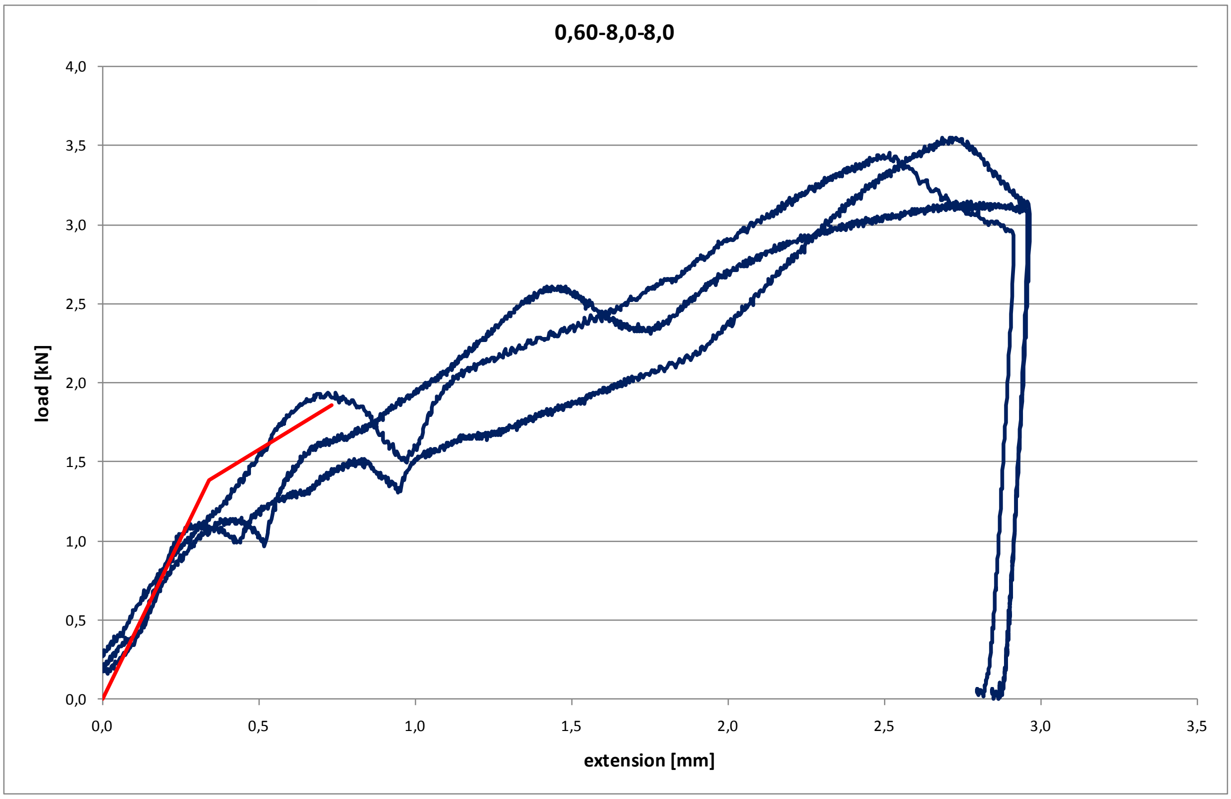

0,60-2,0-5,5
load [kN]
extension [mm]
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5
4,0

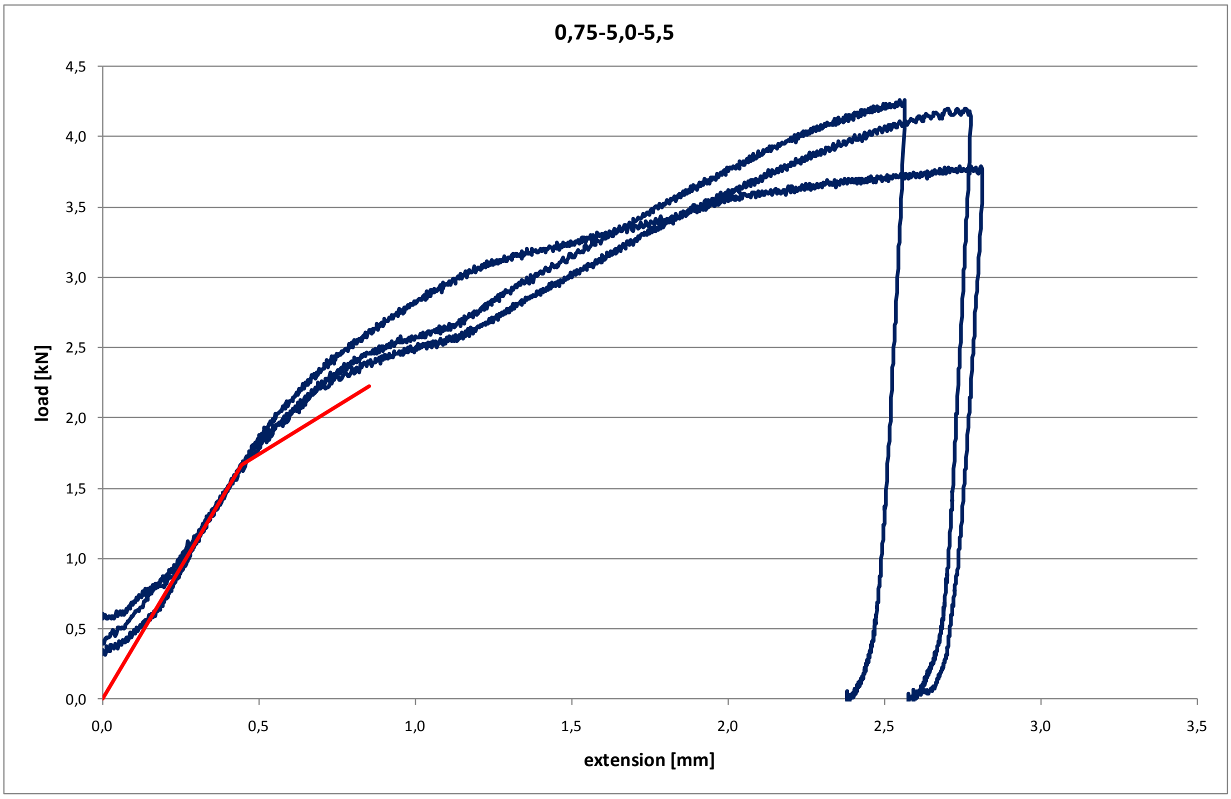

0,60-3,0-6,3
load [kN]
extension [mm]
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5

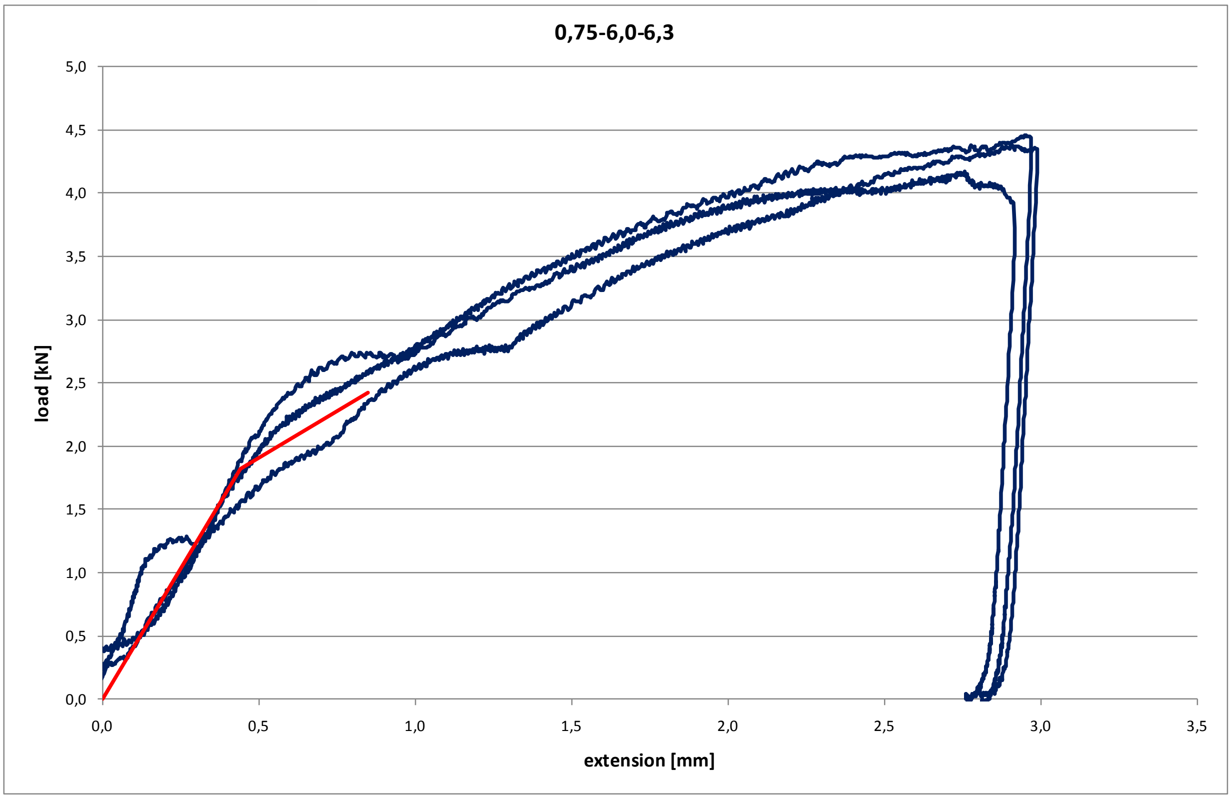

0,60-4,0-8,0
load [kN]
extension [mm]
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5
4,0

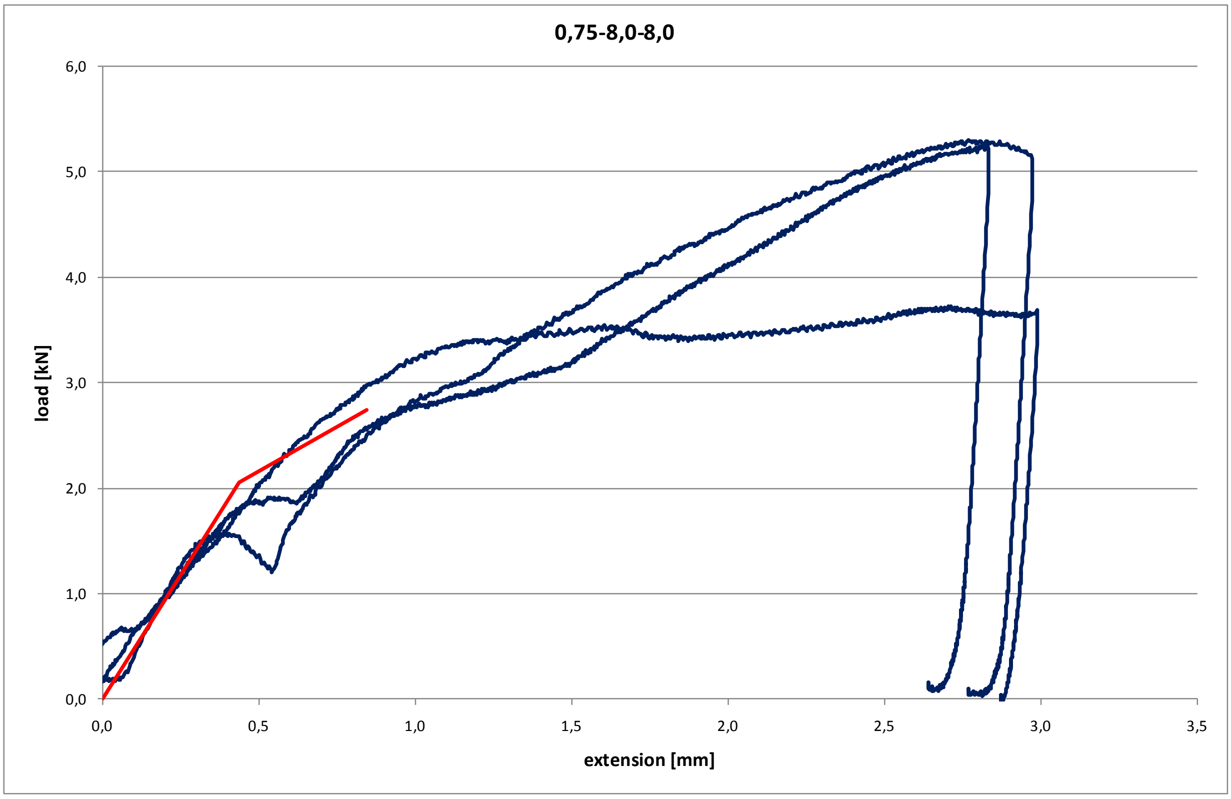

0,60-5,0-5,5
load [kN]
extension [mm]
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5

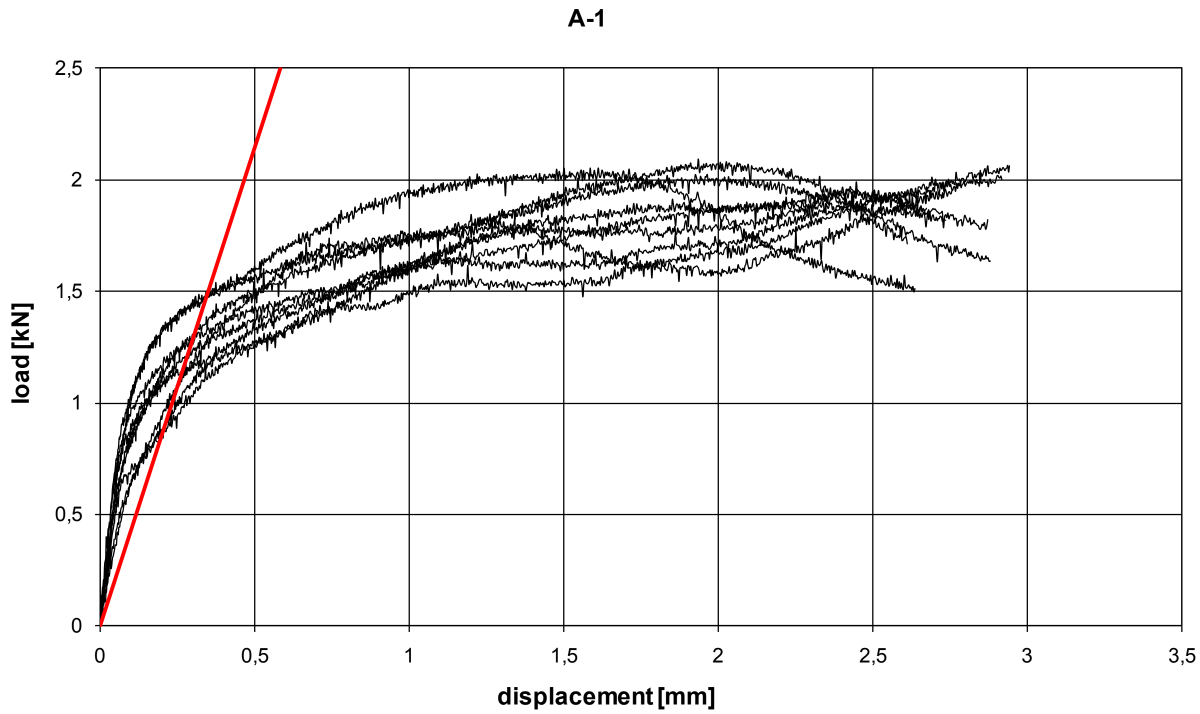

0,60-6,0-6,3
load [kN]
extension [mm]
4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5

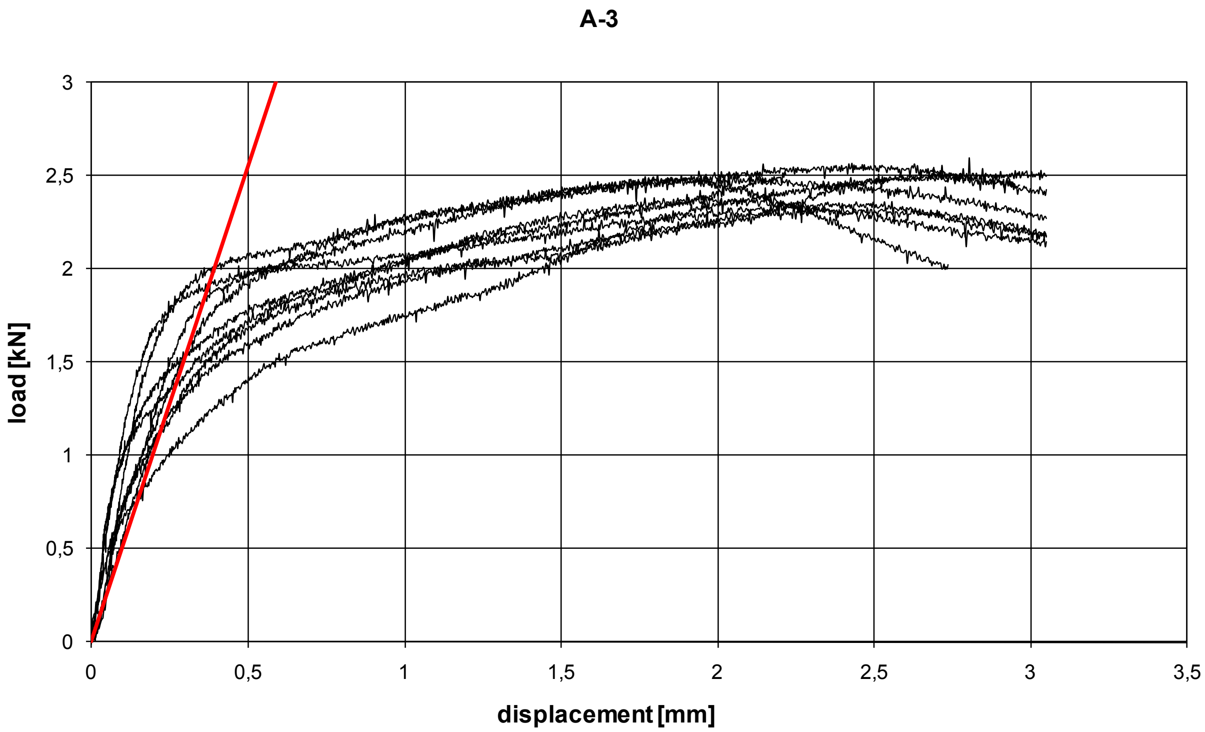

0,60-8,0-8,0
load [kN]
extension [mm]
4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5


0,75-5,0-5,5
load [kN]
extension [mm]
4,5
4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5

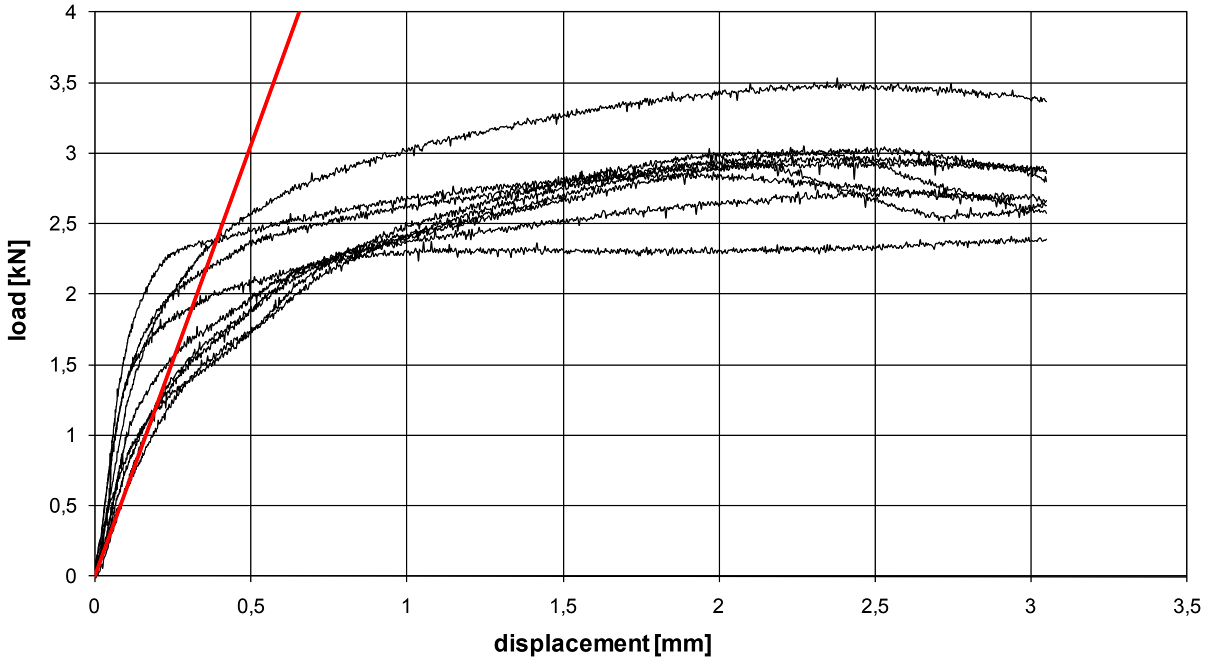

0,75-6,0-6,3
load [kN]
5,0
4,5
4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5
extension [mm]


0,75-8,0-8,0
load [kN]
6,0
5,0
4,0
3,0
2,0
1,0
0,0
0,0
0,5
1,0
1,5
2,0
2,5
3,0
3,5
extension [mm]

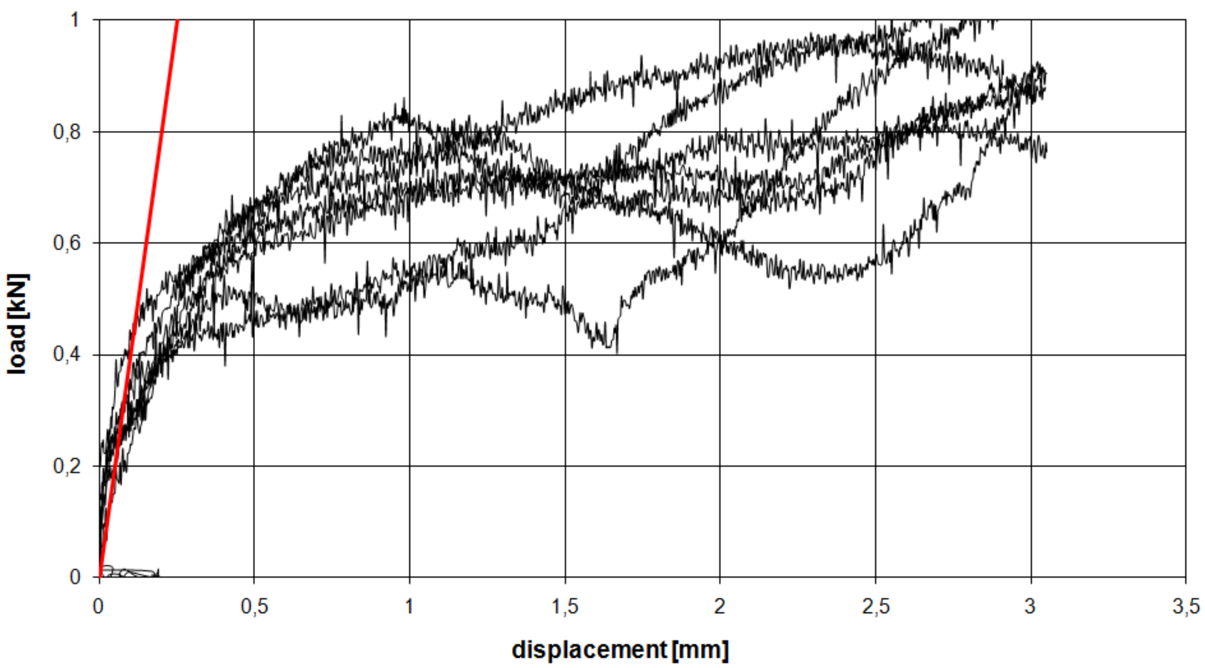

A-1
load [kN]
displacement [mm]
0
0,5
1
1,5
2
2,5
3
3,5


A-3
load [kN]
displacement [mm]
0
0,5
1
1,5
2
2,5
3
3,5

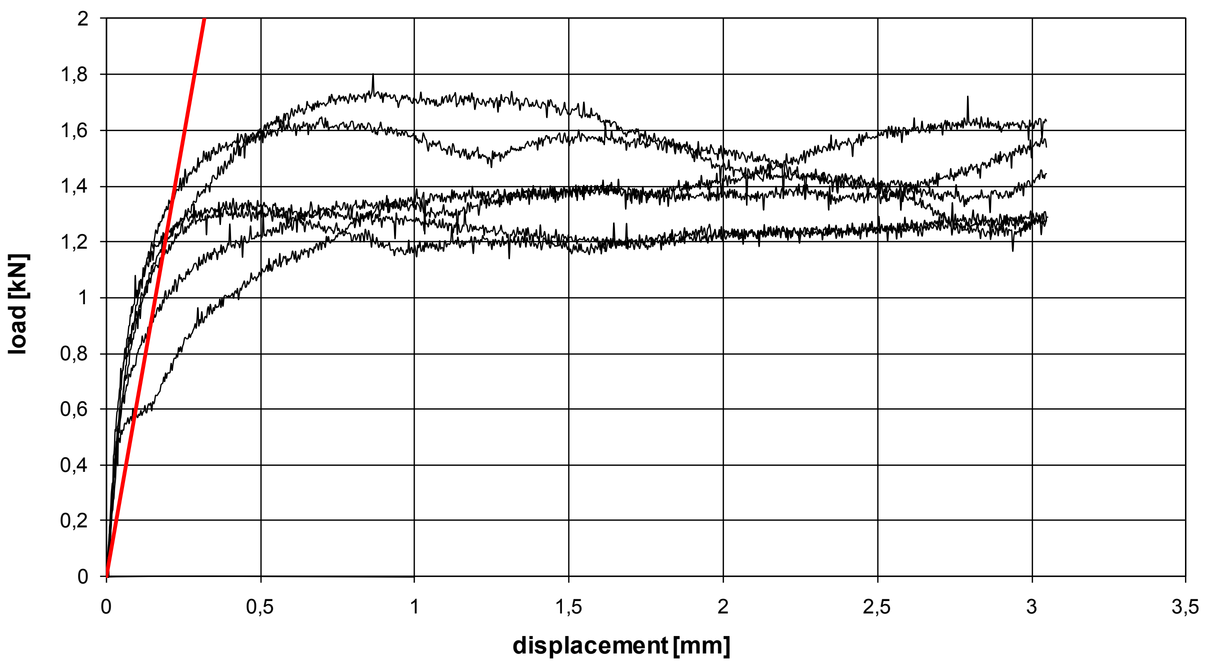
A-3



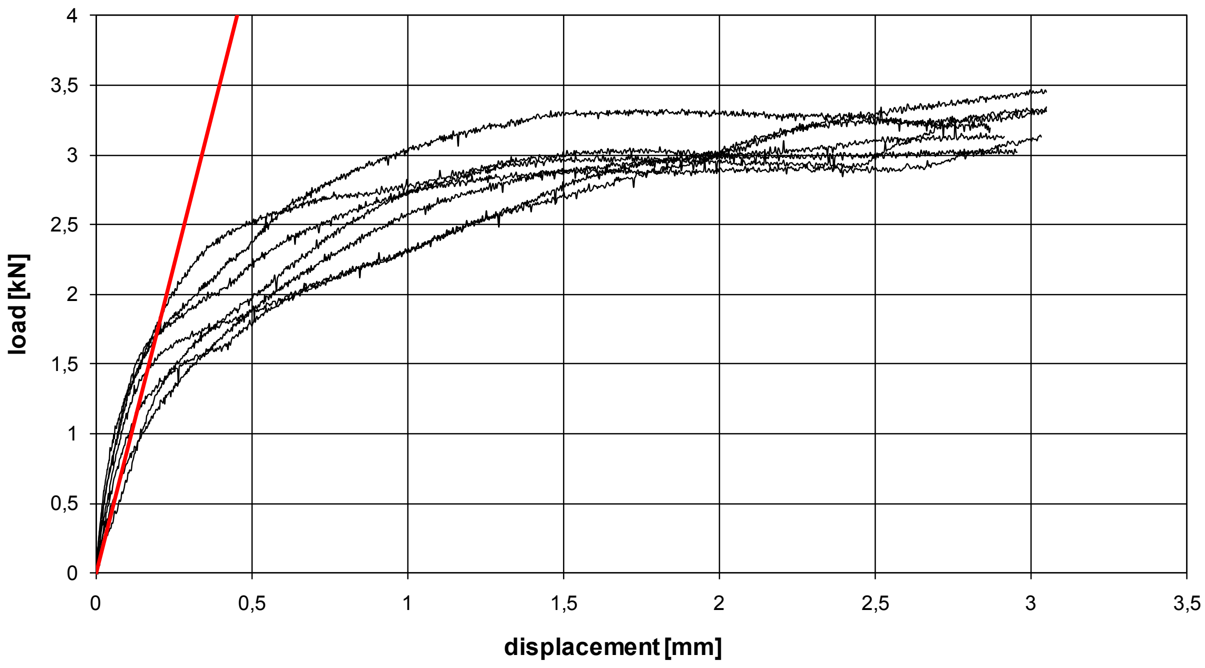
B-1


1
0,8
0,6
0,4
0,2
0
load [kN]
0
0,5
1
1,5
2
2,5
3
3,5
displacement [mm]

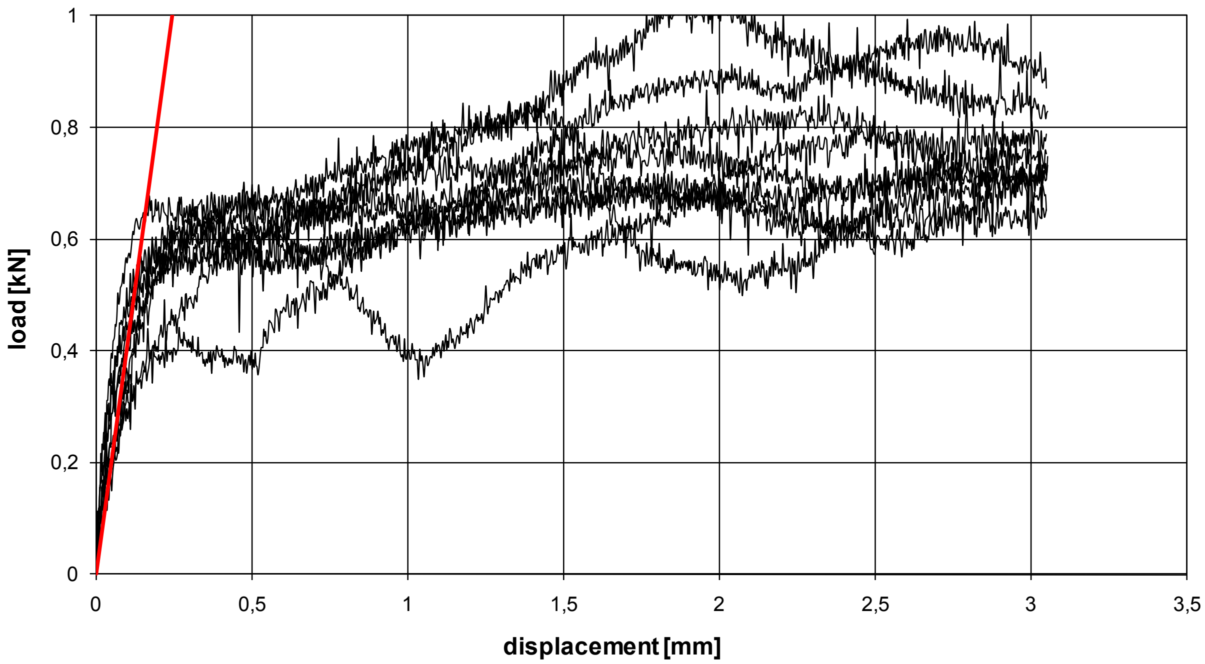
B-2


2
1,8
1,6
1,4
1,2
1
0,8
0,6
0,4
0,2
0
load [kN]
0
0,5
1
1,5
2
2,5
3
3,5
displacement [mm]

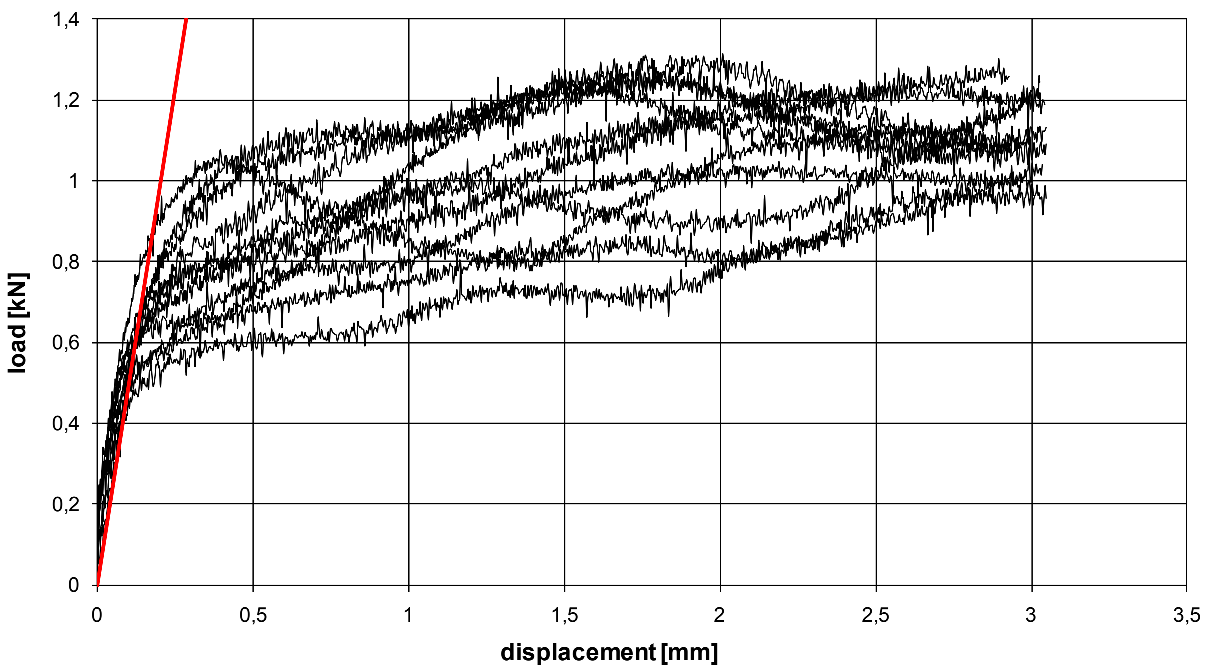
B-3



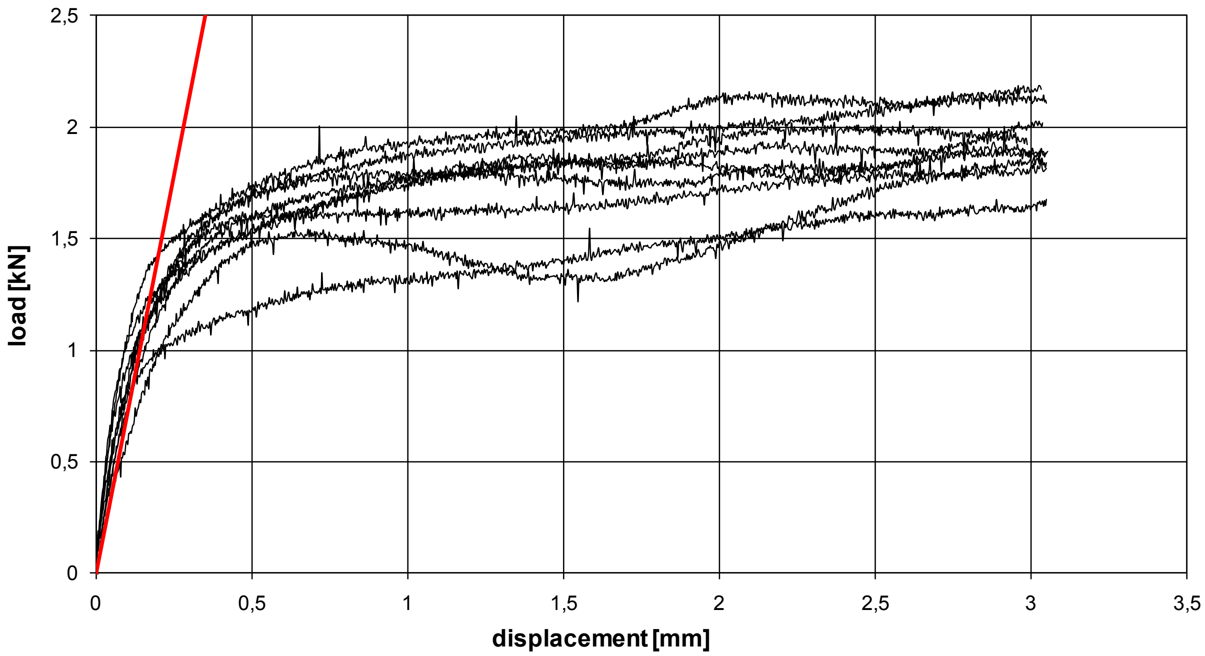
C-1


1
0,8
0,6
0,4
0,2
0
load [kN]
0
0,5
1
1,5
2
2,5
3
3,5
displacement [mm]

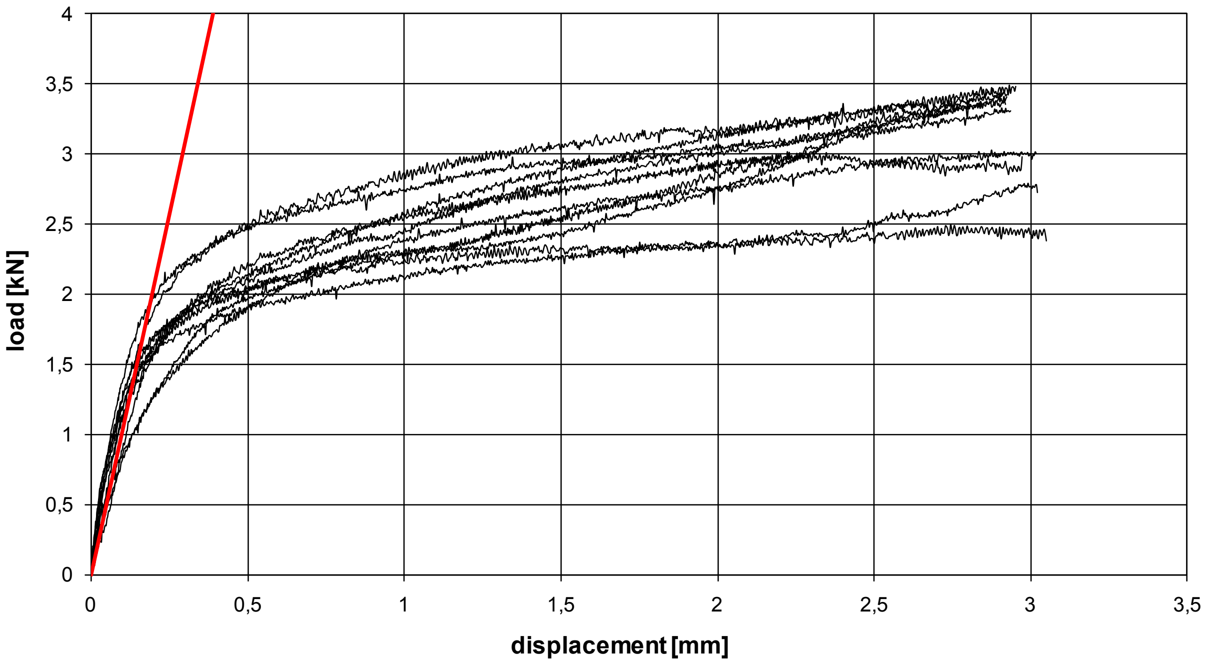
C-2


1,4
1,2
1
0,8
0,6
0,4
0,2
0
load [kN]
0
0,5
1
1,5
2
2,5
3
3,5
displacement [mm]

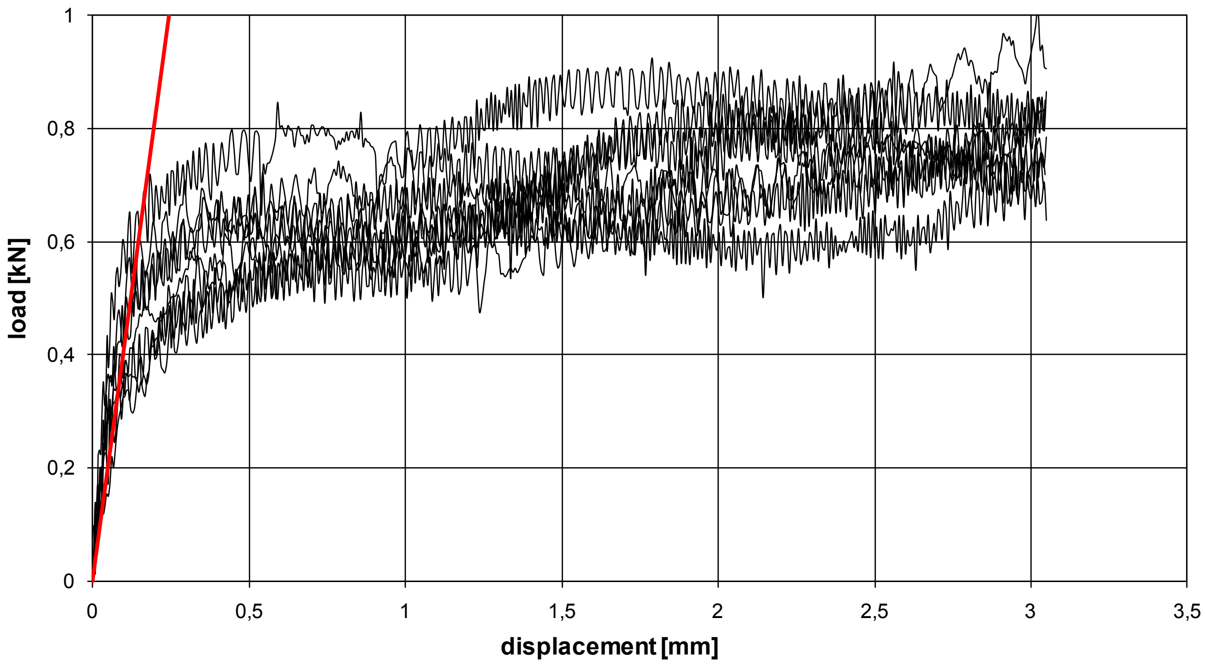
C-3


load [kN]
displacement [mm]
0
0,5
1
1,5
2
2,5
3
3,5

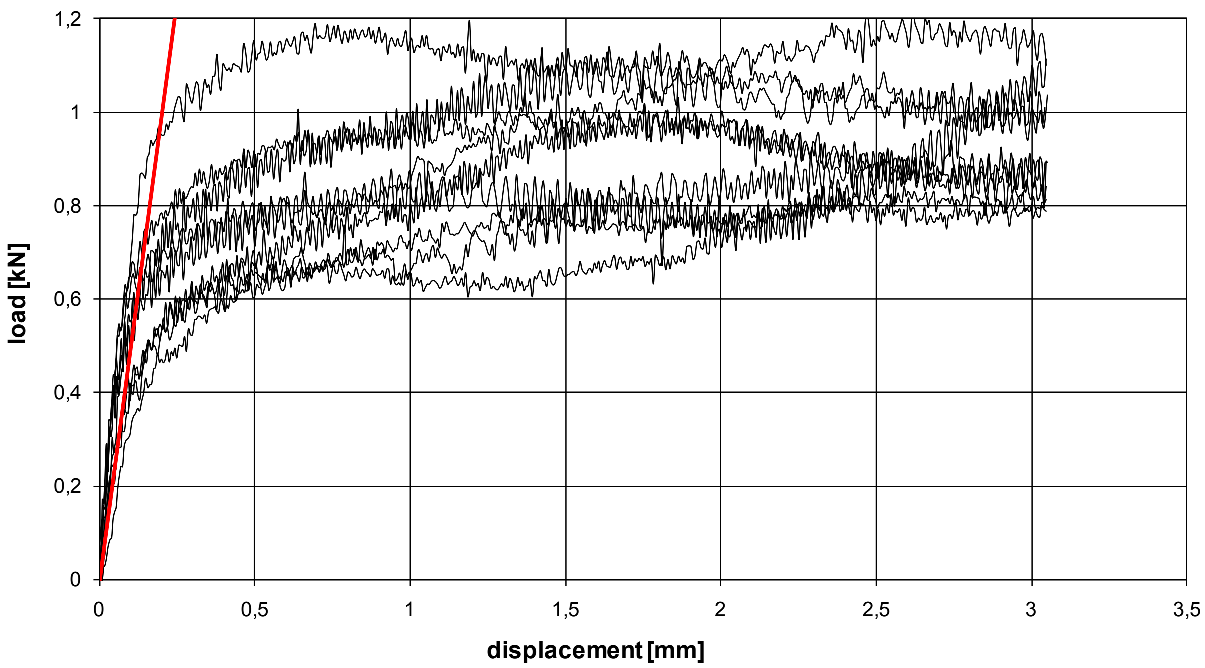
C-4

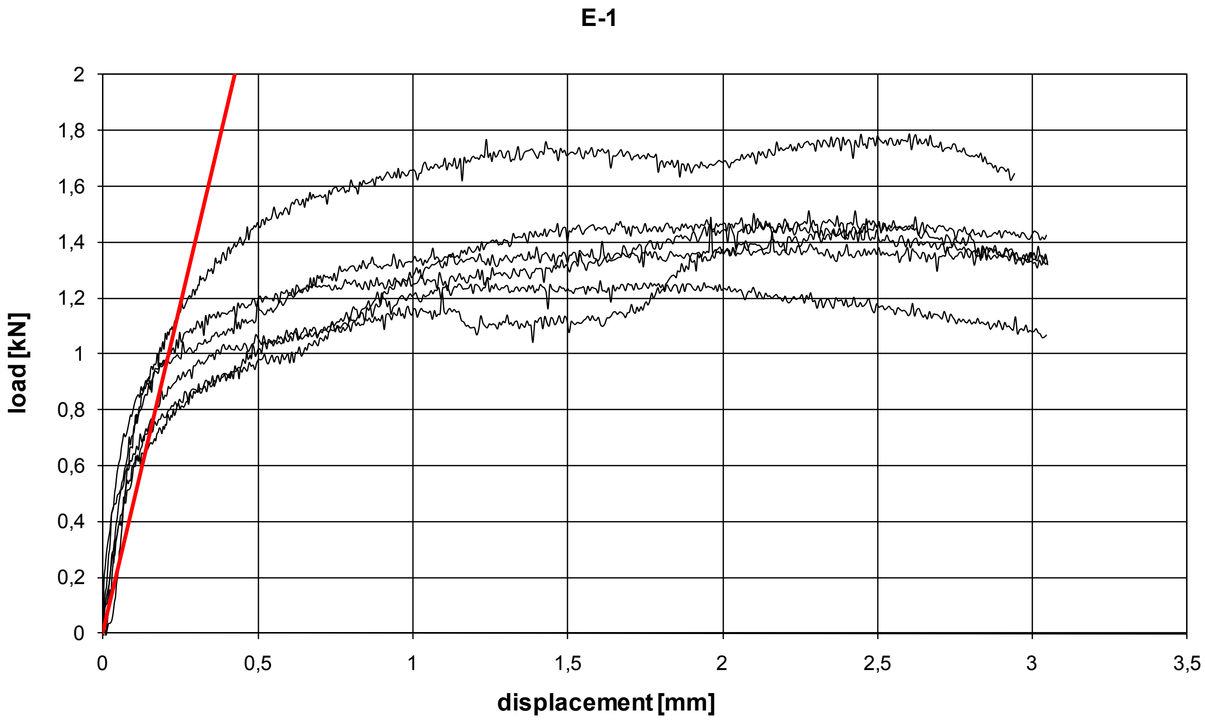

load [kN]
displacement [mm]
0
0,5
1
1,5
2
2,5
3
3,5
4

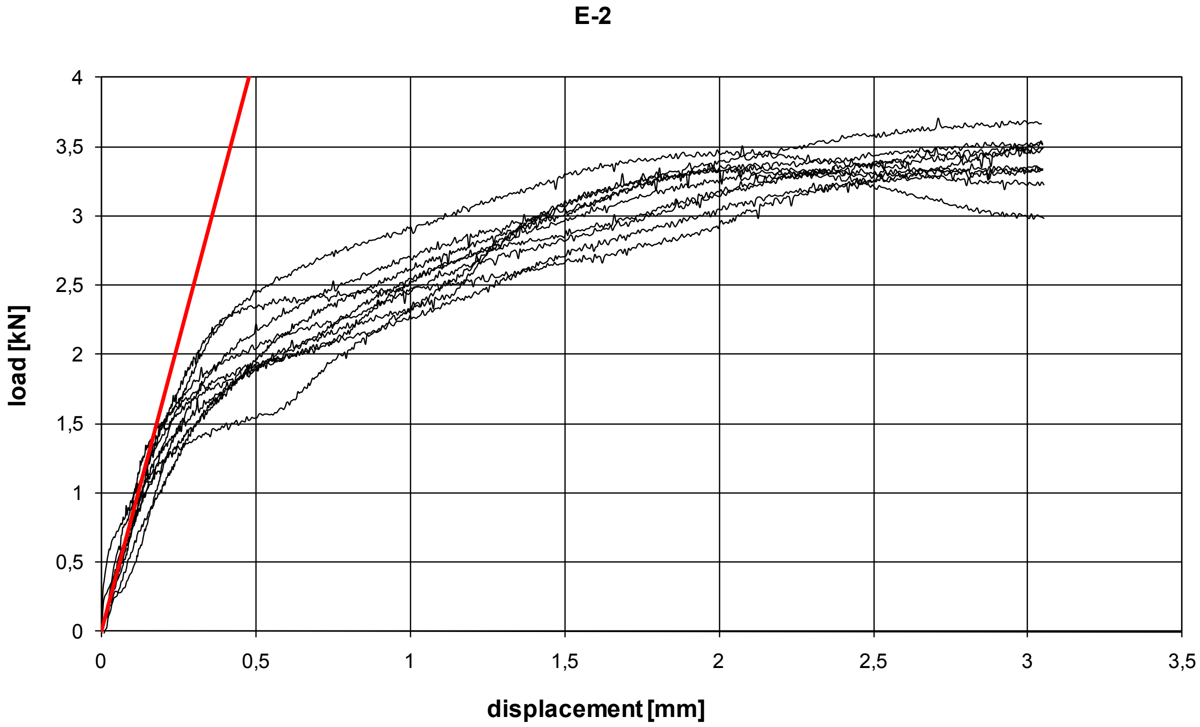
D-1


1
0,8
0,6
0,4
0,2
0
load [kN]
0
0,5
1
1,5
2
2,5
3
3,5
displacement [mm]

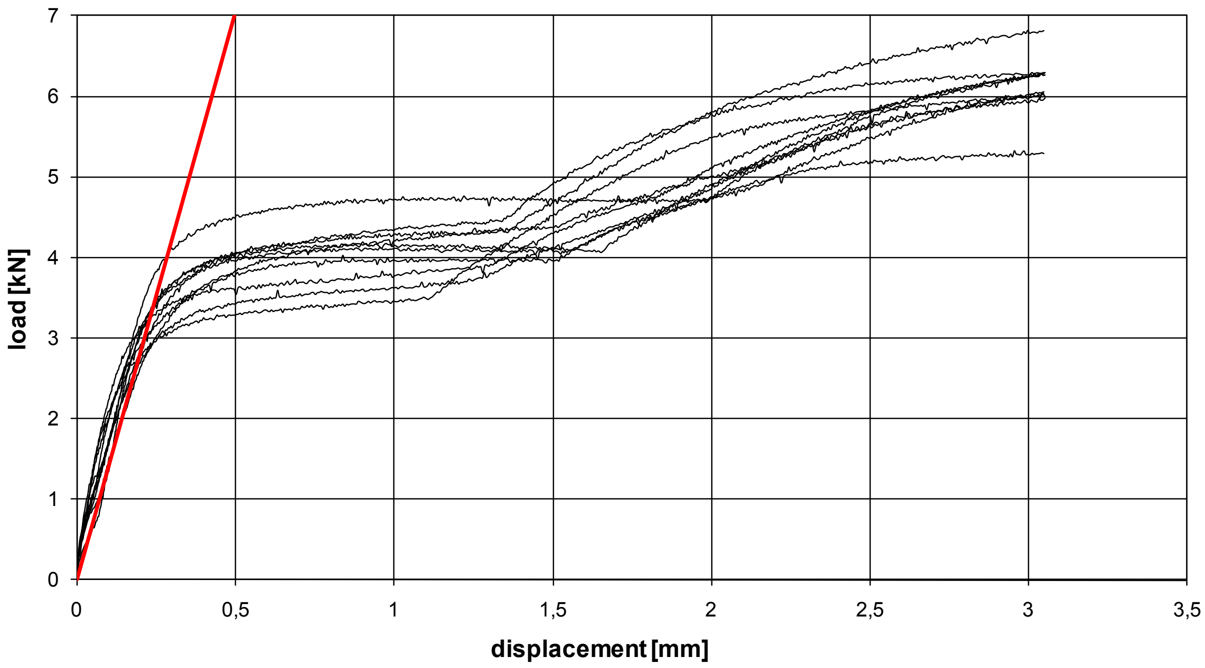
D-2


1,2
1
0,8
0,6
0,4
0,2
0
load [kN]
0
0,5
1
1,5
2
2,5
3
3,5
displacement [mm]

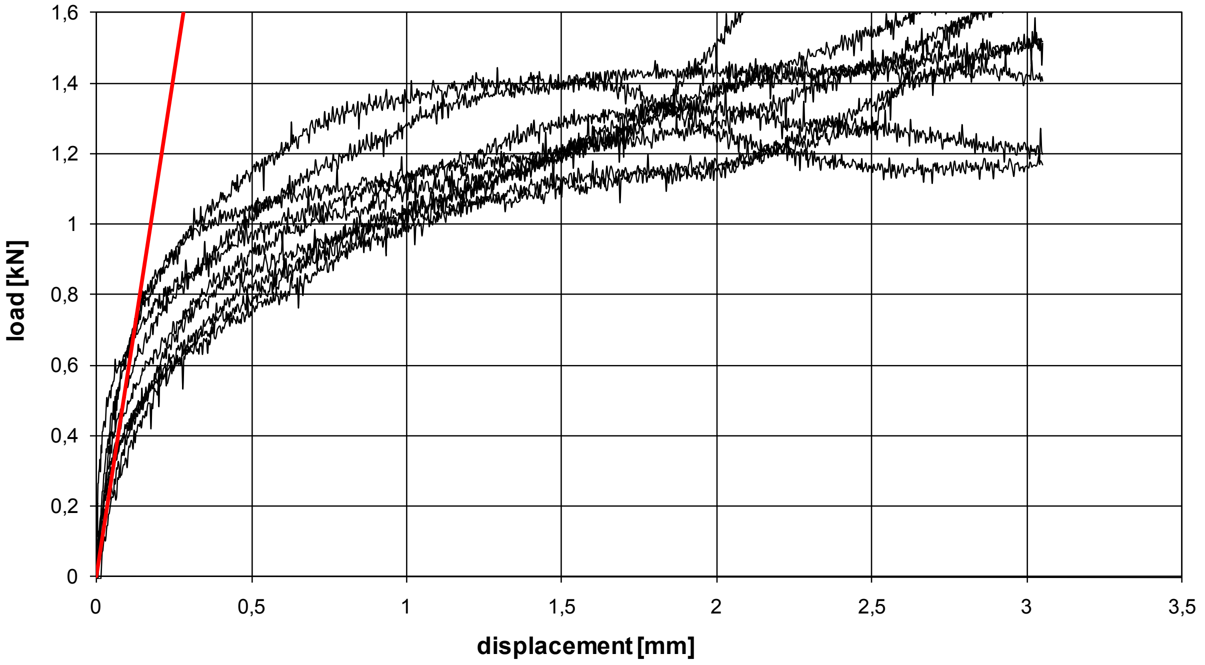

E-1
load [kN]
displacement [mm]
0
0,2
0,4
0,6
0,8
1
1,2
1,4
1,6
1,8
2
0,5
1,5
2,5
3
3,5


E-2
load [kN]
displacement [mm]
0
0,5
1
1,5
2
2,5
3
3,5
4

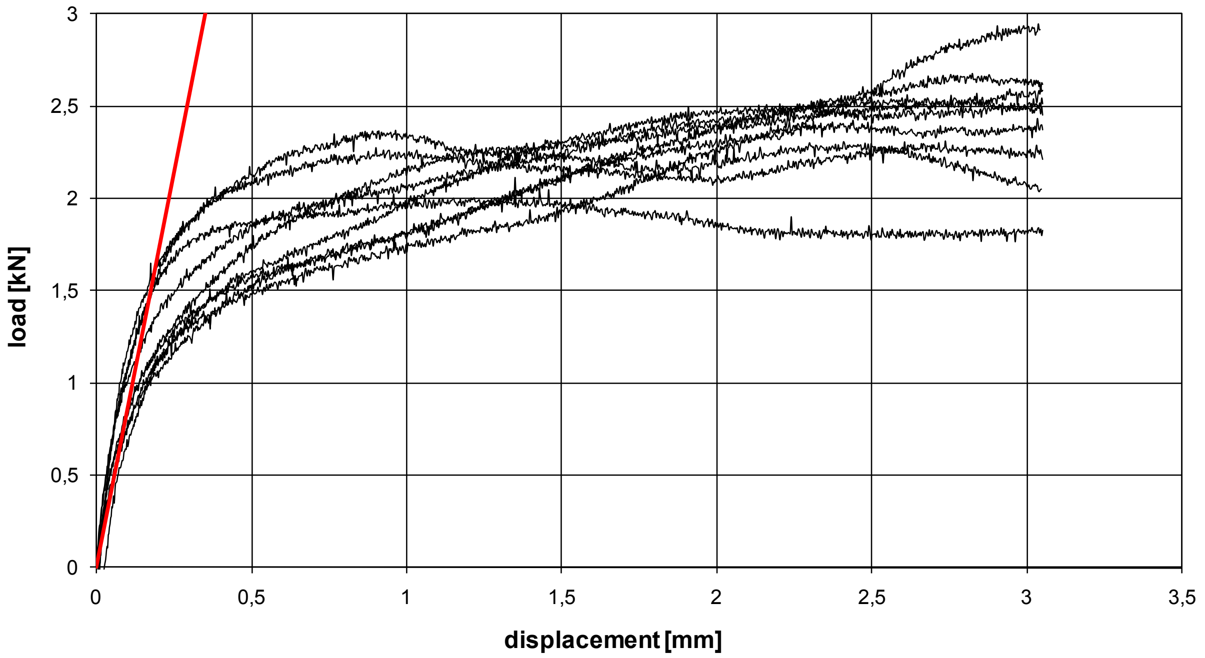
E-3



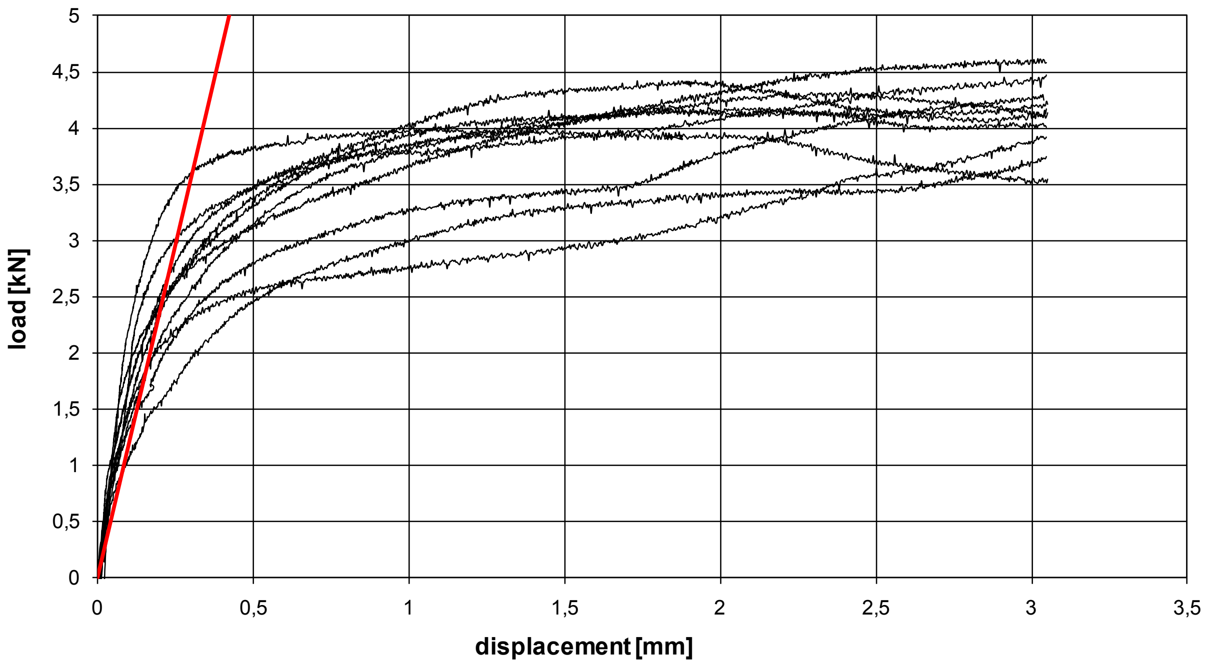
F-1


1,6
1,4
1,2
1
0,8
0,6
0,4
0,2
0
load [kN]
0
0,5
1
1,5
2
2,5
3
3,5
displacement [mm]

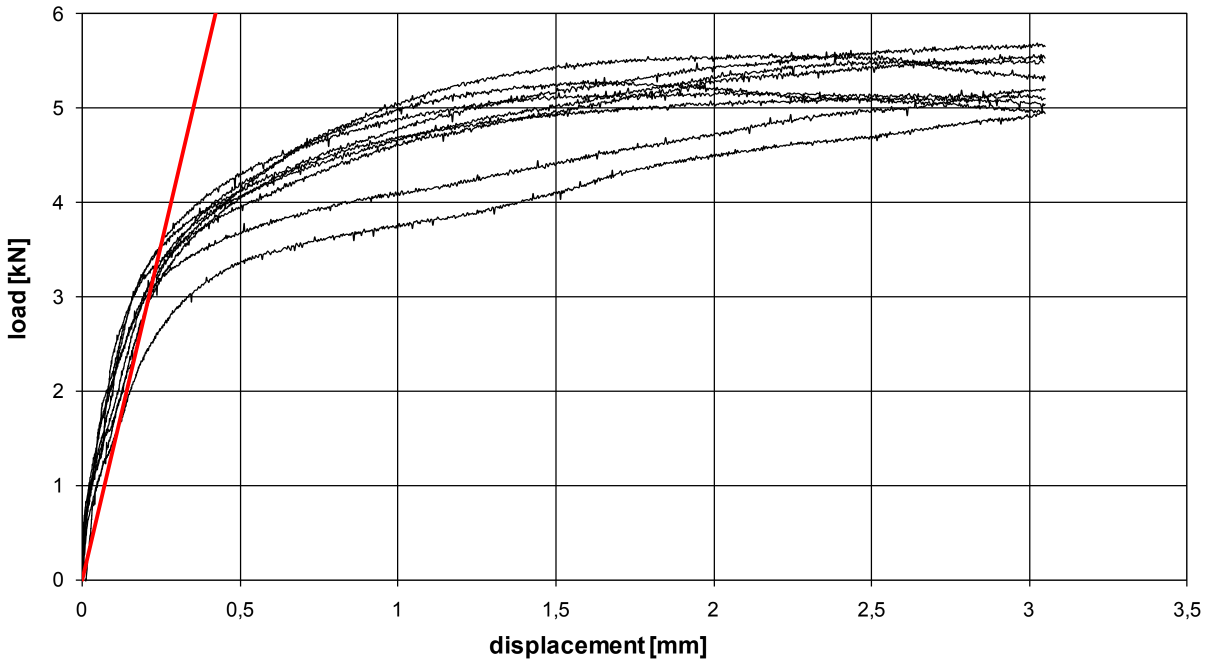
F-2


3
2,5
2
1,5
1
0,5
0
load [kN]
0
0,5
1
1,5
2
2,5
3
3,5
displacement [mm]

F-3


load [kN]
displacement [mm]
0
0,5
1
1,5
2
2,5
3
3,5
4
4,5
5
0
0,5
1
1,5
2
2,5
3
3,5

F-4


load [kN]
displacement [mm]
0
1
2
3
4
5
6
0
0,5
1
1,5
2
2,5
3
3,5

Shear loaded fastenings of sandwich panels - formulary

1 Fastenings of sandwich panels to a steel substructure

1.1 Load bearing capacity

Characteristic value:

$$F_{Rk} = 4{,}2 \cdot \sqrt{t_{F2}^3 \cdot d_1} \cdot f_{u,F2}$$

Design value:

$$F_{Rd} = \frac{F_{Rk}}{\gamma_{M2}}$$

The material safety factor γ_{M2} is given by national specifications. According to EN 1993-1-3 γ_{M2} = 1,25 is recommended. If the load bearing capacity is determined by testing according to different approvals γ_{M2} = 1,33 has to be used.

1.2 Stiffness

$$k_v = \frac{1}{\frac{x_F}{k_{F2}} + \frac{t_{\sup}^2 + 2 \cdot (1 - x_F) \cdot D \cdot t_{\sup}}{4 \cdot C} + \frac{3 \cdot (1 - x_F) \cdot D \cdot t_{\sup}^2 + t_{\sup}^3}{24 \cdot EI}}$$

with

$$x_F = 1 - \frac{\frac{1}{k_{F2}} - \frac{D \cdot t_{\sup}}{2 \cdot C} - \frac{D \cdot t_{\sup}^2}{8 \cdot EI}}{\frac{1}{k_{F2}} + \frac{D^2}{C} + \frac{D^2 \cdot (2 \cdot D + 3 \cdot t_{\sup})}{6 \cdot EI}}$$

Bending stiffness of the fastener

$$EI = 200.000 N/mm^2 \cdot \frac{\pi \cdot d_S^4}{64}$$

Stiffness of clamping in the substructure

$$C = 2400 N/mm^2 \cdot \sqrt{t_{\sup} \cdot d_1^5}$$

Stiffness of internal face sheet (hole elongation)

$$k_{F2} = 6{,}93 \cdot \frac{f_{u,F2} \cdot \sqrt{t_{F2}^3 \cdot d_1}}{0{,}26mm + 0{,}8 \cdot t_{F2}} \qquad 0{,}40mm \le t_{F2} \le 0{,}70mm$$

$$k_{F2} = \frac{4{,}2 \cdot f_{u,F2} \cdot \sqrt{t_F^3 \cdot d_1}}{0{,}373mm} \qquad 0{,}70mm \le t_{F2} \le 1{,}00mm$$

t_{F2} thickness of internal face sheet

t_{sup} thickness of substructure

d_1 minor diameter the threaded part of the fastener

d_S diameter of unthreaded shank

$f_{u,F2}$ tensile strength of internal face sheet

D thickness of panel at point of fastening

1.3 Application range

Fastener:

- Direct fastening, no hidden fastening
- Self-drilling or self-tapping screw
- Nominal diameter 5,5 mm to 8,0 mm
- Stainless steel

Panel:

- Thickness 40 mm to 200 mm
- Thickness of face sheet t_{F2} 0,40 mm to 1,00 mm

Substructure:

- Steel
- Thickness t_{sup} 1,50 mm to 10,0 mm

The stiffness of a fastening given above corresponds to the load level of serviceability loads, which are assumed not to exceed half of the characteristic load-bearing capacity.

2 Fastenings of longitudinal joints

2.1 Load bearing capacity

Characteristic value:

$$F_{Rk} = 3{,}2 \cdot f_{u,F1} \cdot \sqrt{d \cdot t_{F1}^3}$$

Design value:

$$F_{Rd} = \frac{F_{Rk}}{\gamma_{M2}}$$

The material safety factor γ_{M2} is given by national specifications. According to EN 1993-1-3 γ_{M2} = 1,25 is recommended. If the load bearing capacity is determined by testing according to different approvals γ_{M2} = 1,33 has to be used.

2.2 Stiffness

$$k_v = 1900 \frac{N}{mm^3} \cdot t_{F1} \cdot d$$

d nominal diameter of fastener

t_{F1} thickness of external face sheet

$f_{u,F1}$ tensile strength of external face sheet

2.3 Application range:

Fastener:

- Self-drilling screw with sealing washer
- Nominal diameter 4,8 mm to 6,3 mm

Panel:

- Thickness of face sheet t_{F1} 0,40 mm to 1,00 mm

The stiffness of a fastening given above corresponds to the load level of serviceability loads, which are assumed not to exceed half of the characteristic load-bearing capacity.