Stevin - Laboratory
of the Department of
Civil Engineering
of the
Delft University of Technology

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Report 6-72-13
KV-4

High strength bolted beam to column connections. The computation of bolts, T-stub flanges and columnflanges.

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Contents

		page
1.	Introduction	1
2.	Approximate theory	4
3.	Tests described in Stevin Report 6-69-13	10
4.	The test specimens	12
5.	Test procedure	13
6.	Test results and comparison with the theory	14
7.	Concluding remarks	24
	Figures	27
	Diagrams	38
	Appendix A	

1. Introduction

Steel framework often contains connections with bolts loaded by tensile forces due to external loads.
In the following figures some of these connections have been drawn.

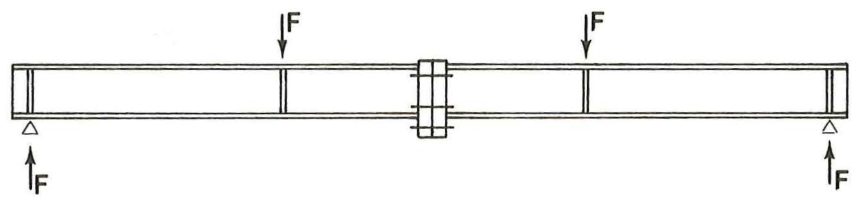


figure 1^a

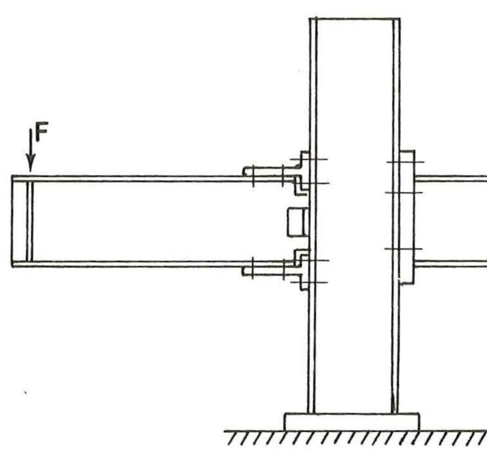


figure 1^b

In the endplate connection of figure 1^a the bolts near the lower flange are subjected to tensile forces, while in figure 1^b the upper flange is the tension side of the beam.
A less complicated connection has been drawn in figure 2. (T-stub connection).
An applied tensile load 2 T must be transmitted. At first glance it might seen that each bolt in this connection will transmit an applied load $\frac{2\ T}{2} = T$.
In practice,the external load of this connection will bend the T-stub flange

(see figure 3). This deflection will cause the flanges to exert pressure on each other. The result is that the bolts must not only transmit the external load 2 T, but also the internal loads Q which develop due to the deflection of the flanges, see figure 4.

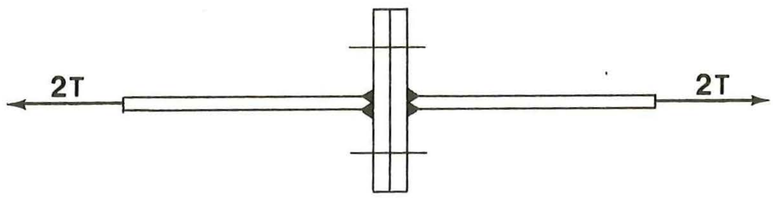


figure 2

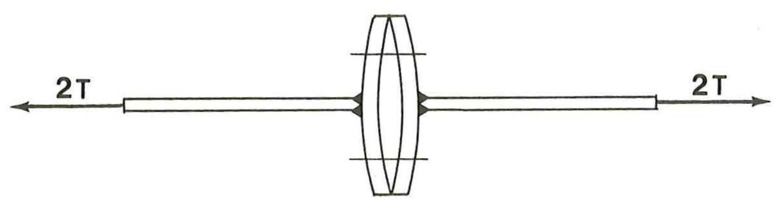


figure 3

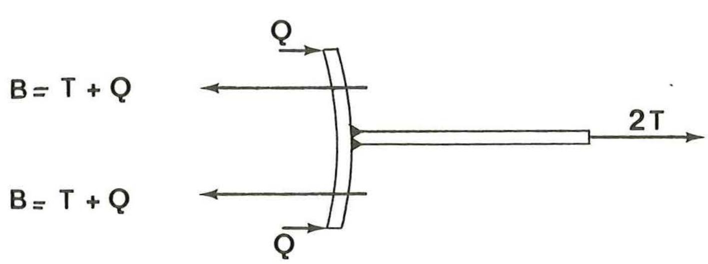


figure 4

In the connection in figure 1^a the planes(flanges) containing the tensile forces are in perfect alignment. In the connections of fig. 1^b the planes (flange of the beam and web of the column) are perpendicular to each other.

An approximation of the available load capacity at the tension side of the connections of figure 1a is obtained by testing specimens as shown in figure 2. (the web of the beam is omitted).

In the tests reported in Stevin-Report 6-69-13: "Tests on high-strength bolted T-stubs with respect to a bolted beam-to-column connection" T-stubs have been tested on a completely rigid base (see figure 5).

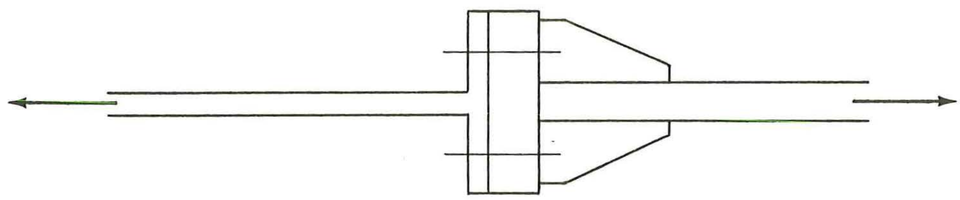


figure 5

In addition to these tests, other connections, shown in figure 3 have recently been tested.

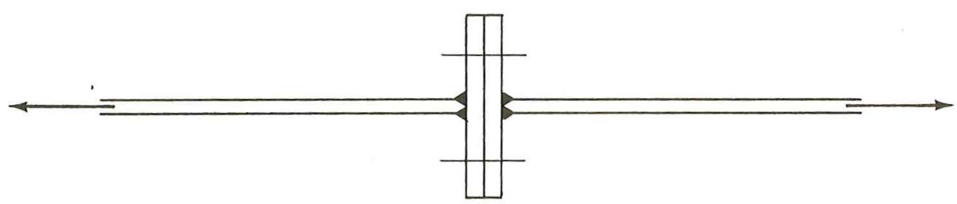


figure 6

The behaviour of the connections of figure 1^b has been tested with test specimens as shown in figure 7.

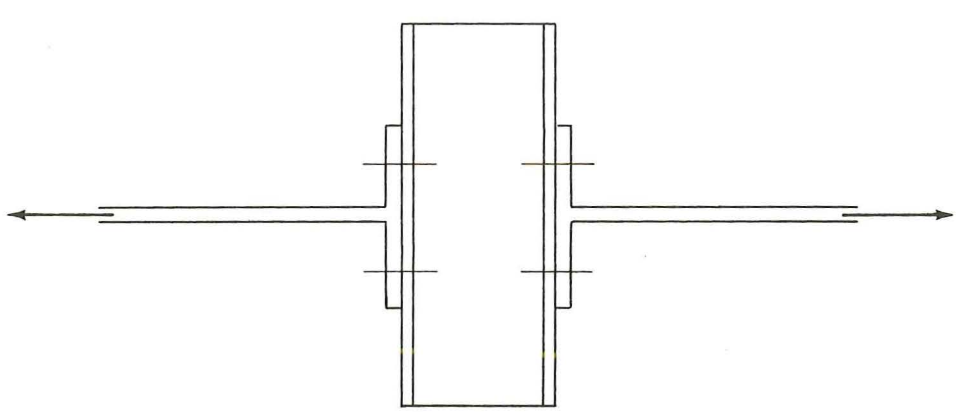


figure 7

The connection of the T-sections shown in the left hand side of figure 1^b corresponds completely to these test specimens while the connection shown in the right-hand side of figure 1^b shows an acceptable resemblance (the web of the beam has been omitted).

Remarks: In this report the computations have been carried out with 1 tf = 10 kN, except in the case of graphs 34 through 54 which have been computed with 1 tf = 9,81 kN.

2. Approximate theory

A method of design for T-stub connections has been developed in report 6-69-13. The results of tests on T-stubs on a completely rigid base indicated that this method seems to be correct.
It was assumed that plastic deformations in the flange-plate and the bolts will occur before the construction collapses. A modified version of this method of design is now given.
It is assumed that simple plasticshinges could form at the inner end of the span m (see figure 8) and at the bolt line, with the respective values

$$M_v = \frac{b\,t^2\,\sigma_v}{4} \quad \text{and} \quad M_v' = \frac{k\,bt^2\,\sigma_v}{4}$$

in which k is a reduction factor to allow for the presence of the bolt holes ($k = \frac{\text{nett area}}{\text{gross area}}$). The collapse mechanisms which could form are subdivided in mechanisms A, B and C in figure 8 on page 5.
In mechanism A a prying force does nog occur.
In mechanism B a prying force, Q, is assumed to exert pressure at the ends of the span n.
In mechanism C the force, Q, at the ends of the span, n, reaches its maximum value and causes a plastic hinge to form at the bolt lines in the flange-plate. The force distribution, moment line and line of shear forces belonging to the three collapse mechanisms have also been drawn in figure 8. B_u = the total ultimate tensile load of the bolts fitted at one side of the tensile strip. (web of the T-section).
T = the half of the tensile load applied to the construction
Q = the prying force between the flange-plate and the support. It is assumed that this force acts on the ends of the spans.
M_v = the plastic moment that causes a plastic hinge to form, immediately adjacent to the tensile strip (gross area).
M_v' = the entire plastic moment that causes a plastic hinge to form at the bolt line (weakened section) (nett area)

$$M_v' = \frac{\text{nett area}}{\text{gross area}} \cdot M_v$$

Remark: by calculating the plastic moment the shear forces have been neglected:

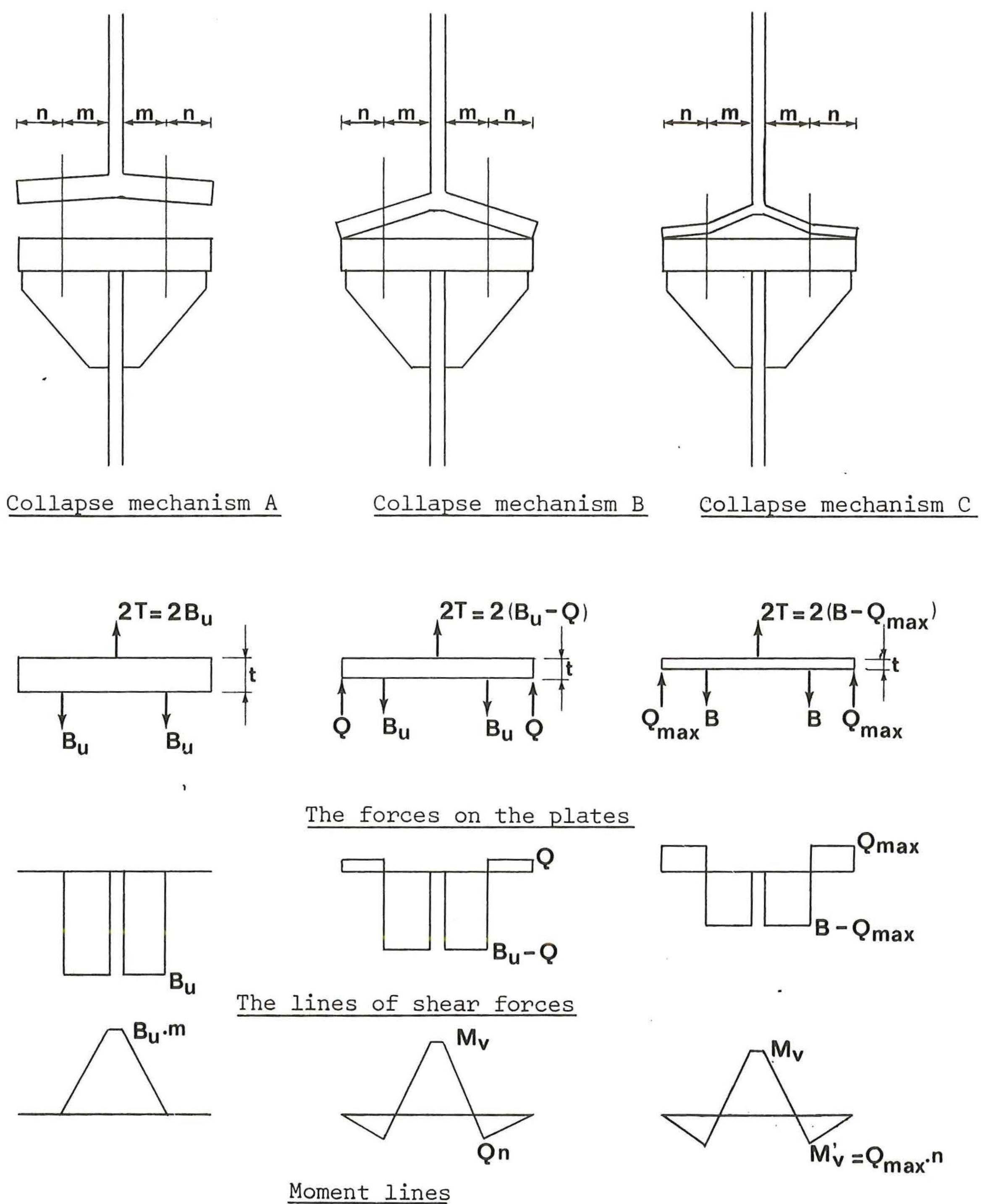


Figure 8

For compution purposes, the collapse mechanism A and C could be considered as extremes ($Q = 0$ respectively $Q = max.$) of mechanism B.

Collapse mechanism B (the bolt fracture is the determining factor).

A plastic hinge is formed next to the tensile strip before the ultimate tensile load of the bolt has been reached. At the ends of the spans, n, a force, Q, developes which decreases the ultimate tensile load T, because $T = B_u - Q$. There will either be no plastic hinge at the bolt line or this hinge will have been formed simultaneously with the rupture of the bolt.

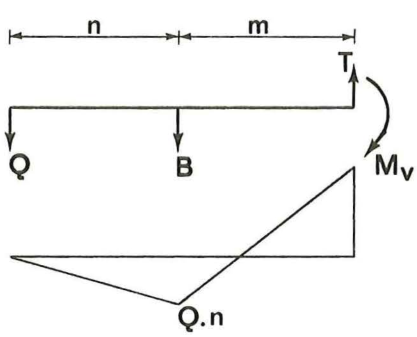


figure 9

T = the ultimate tensile load of one side of the connection.

B_u = the total ultimate tensile load of the bolts fitted at one side of the connection.

M_v = $\frac{1}{4}\, b\, t^2\, \sigma_v$ is the plastic moment that causes a plastic hinge to form.

b = the width of the flange plate.

t = thickness of the flange plate.

σ_v = yield stress.

Therefore, the following hold for collapse mechanism B:

$$\left.\begin{array}{l} T = B_u - Q \\ T \times m - Q \times n = M_v \end{array}\right\} \text{ these two relations combined in one formula yield}$$

$$T \times m - (B_u - T) \times n = M_v \qquad \text{------------------} \qquad (1)$$

If $Q = 0$, than collapse mechanism A will come into being. (the bolt fracture is the determining factor).
The flange is heavy with respect to the rigidity of the bolt.
There will either be no plastic hinge next to the tensile strip (web of the T-section) or this hinge will have been formed simultaneously with the failure of the bolts. Therefore, for this mechanism, it holds that:

$$T \times m \leq M_v$$

which follows directly from

(1) because, $B_u = T$

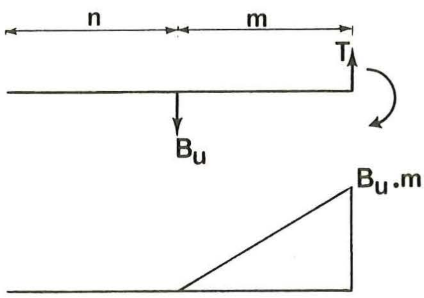


figure 10

If, Q, reaches its maximum value, then collapse mechanism C (the flange-plate is the determining factor) will come into being.
The prying force, Q, reaches its maximum value when a plastic hinge has been caused to form at the bolt line.

$$Q \times n = M_v'$$

$$Q_{max} = \frac{M_v'}{n}$$

Now formula (1) changes to

$$T \times m - \frac{M_v'}{n} \times n = M_v$$

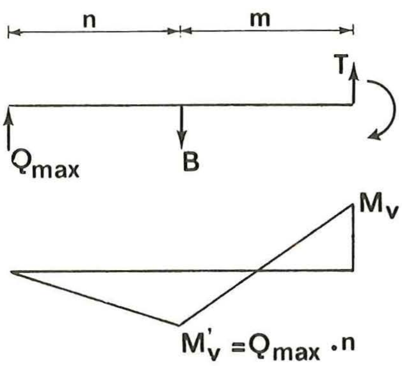


figure 11

$5^e \rightarrow X$ $\quad T \times m = M_v + M_v'$ ----------------------- (2)

in which $M_v' = \frac{\text{net area flange-plate}}{\text{gross area flange-plate}} M_v$

In this case the flange-plate is the determining factor.
Now $T = B - Q$, but B will be equal to B_u, only in the optimum case. B is the bolt force immediately prior to the formation of a plastic hinge at the bolt line. In other words increasing the bolt-diameter certainly yields a larger, B_u, but not a larger, T.,

$X\ 5^e$

Remarks:

In summarizing, the next points are important. At constant, T, and increasing, Q, the ultimate tensile load of the bolt, B_u, must also increase (B_u = T + Q) (a larger bolt diameter is necessary) as a result of which the flange-plate thichness may decrease.

$$(T \times m - Q \times n = M_v = \frac{1}{4} b\, t^2\, \sigma_v)$$

If Q=0,than T = B_u but the flange-plate thickness is determined by T x m = M_v. This gives the maximum required thickness of the flange-plate and the smallest bolt.
If one takes $Q = Q_{max} = \frac{M_v'}{n}$, than

$$T \times m = M_v + M_v' = \frac{\text{gross width + net width of the flange plate}}{\text{gross width}} M_v$$

from which the minimum required thickness of the flange-plate follows at given, T, but the largest bolt.
The deformations immediately prior to the collapse are the determining factors for the ultimate load of the connection.
With a heavy flange plate, for example,the initial deflection of the flange plate might be larger than the elongation of the bolts. In this stage there might be a prying force. However, immediately prior to the collapse, the elongation of the bolts is larger than the deflection of the flange plate. So there is no prying force at that moment, and the bolt force is equal to the external load.
Assuming now that the assumed collapse mechanism at which $0 \leq Q \leq Q_{max}$ really occurs (in other words the plastic behaviour of flange-plate and bolt is such that the collapse mechanism adapts to the computation) then, adopting load factor,design and control of a connection have to agree with the following two conditions:

$$T \times m - (B_u - T)\, n \leq M_v \qquad (1) \qquad (B_u - T \geq 0)$$

$$T \times m \leq M_v + M_v' \qquad (2)$$

This means, in fact, that one is free to choose the desired collapse mechanism and consequently plate thickness and bolt diameters within certain limits (see foregoing Remarks)

The objection to formulas (1) and (2) is that on the one hand one computes with the ultimate load of the bolt and on the other hand with the plastic moments of the plate.
It would be more correct to include the yield strength of the bolt too.
For the high-strength steel of the bolt it is not quite clear which strength should be taken.
For bolts with quality 10.9, the yield strength is 0.9 of the ultimate strength, but the T.G.B. '70 (Dutch Standards) requires that no more than 0.7 of the ultimate strength will be taken into account. To compute with the plastic moment the T.G.B. '70 stipulates that one has to use a loadfactor of 1.5 but the required safety (load factor) against failure for bolts with quality 10.9 is 2 according to the "Voorlopige richtlijnen voor het ontwerpen en de uitvoering van verbindingen met voorspanbouten in staalconstructies"
(Dutch Standards, translation).
Provisional directions for the design and execution of connections with high-strength bolts in steel constructions.)
Taking into account these load factors, viz. a load factor 1.5 for the yield-point moment, and a load factor 2 for failure, the formules (1) and (2) have to be transformed into:

for the ultimate limit state with a load factor of 2 (rupture of the bolt)

$$\left.\begin{array}{ll} T \times m - (B_u - T)n \leq 4/3\ M_v & (1a) \\ T \times m \leq 4/3\ (M_v + M_v') & (2a) \\ (B_u - T) \geq 0 & \end{array}\right\}$$

In these formulas T = the computed tensile force with a load factor 2.

for the limit state of great deformations (yielding) with a load factor of 1.5 (yielding of the bolt)

$$\left.\begin{array}{ll} T \times m - (3/4\ B_u - T)n \leq M_v & (1b) \\ T \times m \leq M_v + M_v' & (2b) \\ (3/4\ B_u - T) \geq 0 & \end{array}\right\}$$

In this formulas T = the computed tensile force with a load factor 1.5.

In this case it is assumed that the yield strength of the bolt equals 3/4 the ultimate tensile strength, (see (1b) and that at failure of the bolt the moment in the plate has increased to 4/3 M_v (M_v = plastic moment) (see (1a) and (2a))*

The design with a load factor 1.5 can now be made using formulas (1b) and (2b). In this case a safety factor of $\frac{1.5}{3/4} = 2$ against failure (load factor) is present.

(Some examples of computation are given in appendix 1). Formulas (1a) and (2a) have been used for the tests in which the ultimate tensile loads have been determined.

3. Tests described in Stevin Report 6-69-13

The results of the tests described in Stevin report 6-69-13 has been compared with calculations carried out with the above-mentioned formulas (1a) and (2a). The test specimens had the same main dimensions as drawn in figure 12 (see page 27).

The computation gave the results as reported in the next tabel.

In this tabel the characters A,B and C conform to the collapse mechanism described in figure 8 determined by the computation.

T/B_u is that part of the ultimate load of the bolt having useful effect of efficiency for the purpose of supporting the applied tensile load, T,.

The remaining part of the ultimate load has been used to support the prying force, Q,.

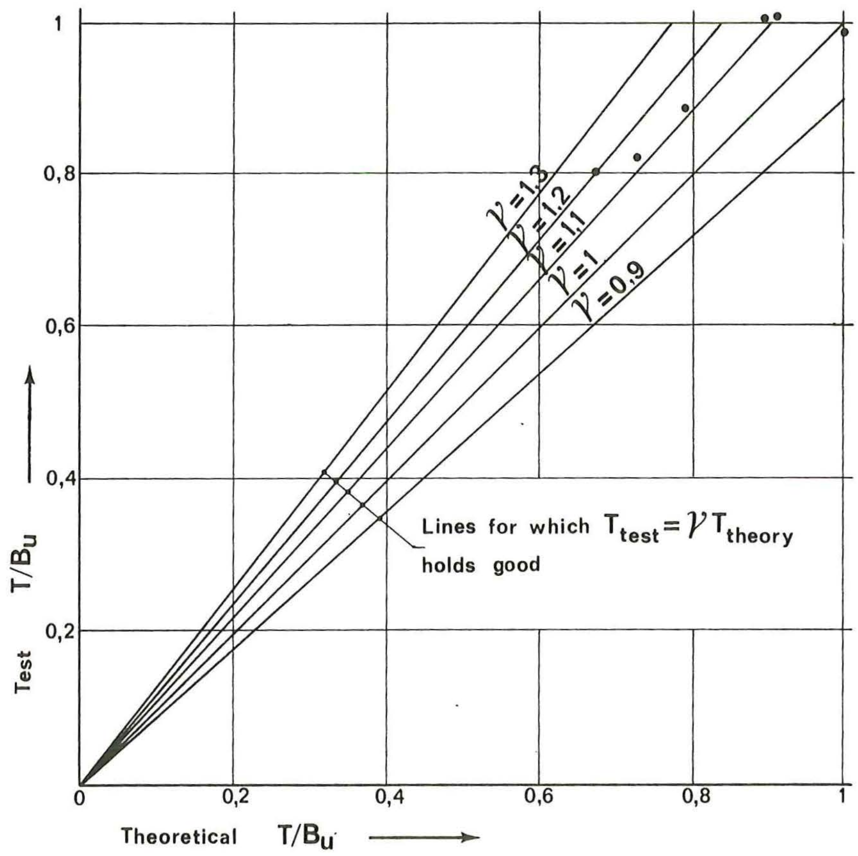
* The factor 4/3 can be explained by:

a) strain hardening in the plastic hinge
b) clipping of the moment line due to the diameter of the bolts
c) second-order effects (developments of tensile forces in the plate)

Plate dimensions	Test			Computation			
	2T	$2B_u$	T/B_u	2T	$2B_u$	T/B_u	A,B or C
t = 16 mm m=3,2cm n=2,4cm	56,7	70,1	0,80	46,8	70,1	0,67	B
t = 17mm m=3,2cm n=3,2cm	58,5	70,1	0,83	52,2	70,1	0,74	B
t = 20 mm m=3,2cm n=3,2cm	63,6	72,0	0,88	56,4	72,0	0,78	B
t = 25 mm m=3,2cm n=3,2cm	72,2*	70,7*	1,02	64,2	70,7	0,91	B
t = 25 mm m=3,2cm n=2,4cm	71,2*	70,7*	1,01	63,2	70,7	0,90	B
t = 32 mm m=3,2cm n=3,2cm	67,0*	68,6*	0,98	68,6	68,6	1,00	A

* The ultimate load, B_u, has been determined by taking the average ultimate load of a number of fractured bolts.
Small differences between B_u and T might be caused by incidental differences from the average.

The above-mentioned results have been plotted in the following graph in order to give an indication of the conformity between the testresults and the computation.



The line $\gamma = 1$ ($T_{test} = T_{theory}$) has a 45° angle of incline, and is the line joining all points if the theory agrees with the test results. If $\gamma > 1$ than $T_{test} > T_{theory}$, and one can ascertain that the test results have an extra "safety", γ, with respect to the theory.

4. The test specimens

The main dimensions and the number of test specimens have been given in the figures 12, 13 and 14.
In figure 12 (page 27) the test specimens with a variable thickness of the flange-plate has been drawn. The tensile strips are in alignment with each other.

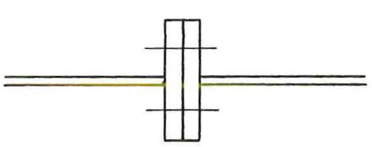


figure 15

The figures 13 and 14 (page 28 and 29) show the test specimens of which the tensile strips are not in alignment.
(t is variable, the test specimens in figure 13 have a centre piece, HE 240 B, and those in figure 14 have a centre piece HE 160 M).

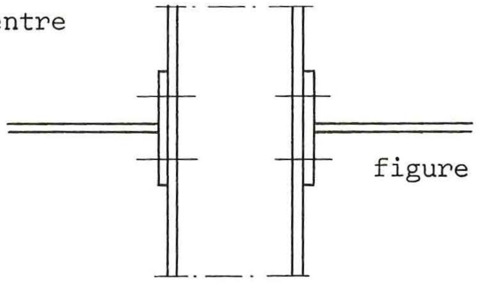


figure 16

All test specimens have been carried out with Fe 37 (Fe E 24) with a theoretical yield - point of 240 N/mm^2.

The thickness of the flange plate has been chosen in such a way as to further the occurrence of all three collapse mechanics, A (Q = 0), B and C (Q = max.).

Remarks: During the tests it appeared that the T-stub flanges with t = 17 mm and t = 20 mm had a yield-stress and a ultimate stress, corresponding to that of Fe 52.
Since the thinnest plate, t = 17 mm, was exactly the point at which the collapse mechanism C(Q = max and so two plastic hinges at one side) had to occur, the high yield stress made it impossible.

5. Test procedure

The test procedure consisted of the following parts:

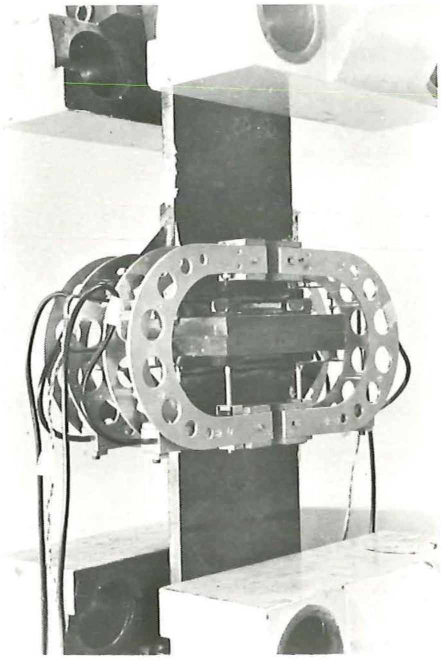
a) Before the high-strength bolts were used they had all been calibrated in a testing machine with a maximum load capacity of 200 kN up to the specified proof load with the grip of the bolt equal to that in the test specimen.

b) Extra bolts (4) supplied with each batch used in the tests have been calibrated to determine an average load elongation curve for each particular batch.
For this purpose the bolts have been placed in a testing machine with the grip of the bolt to be calibrated equal to that of the corresponding bolts used in the test specimens; The load of the bolts has been increased step by step,and at each step the elongation of the bolt has been measured using an extensometer (see photograph).
See pages 59 through 68 for the average load elongation curves.

c) In assembling the T-stub specimens all bolts have been tightened with hand wrenchess until the specified proof load of 113 kN, determined by elongation readings, was reached.

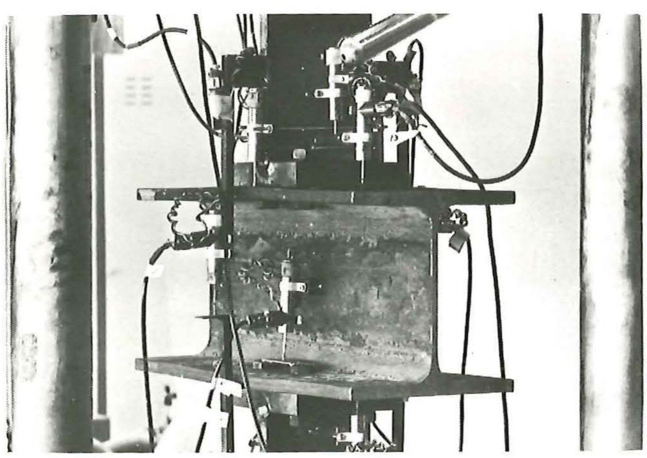
d) All tests have been conducted in a normal universal testing machine with a maximum load capacity of 1000 kN.
The bolt elongations and the deformations of various parts of the specimen have been measured at several stages during the testing of the specimens.

The extensometer used consisted of a rigid frame with leaf springs provided with strain gauges (see photograph). Elongation of the bolt causes the



Extensometers placed on the bolts

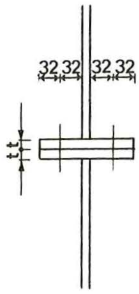
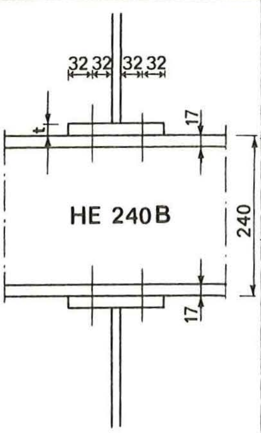
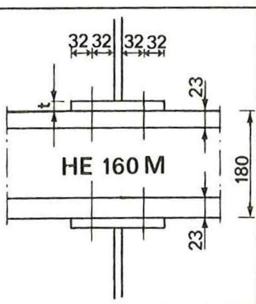
leaf springs to bend. The changing of the electrical resistance of the strain gauges due to this bending served as a measure of bolt elongation.
The deformations of the test specimen have been measured with linear displacement transduces (see photograph). The use of these extensometers and induction meters had the advantage over the normal dial instruments that all information concerning the bolt elongations and the other displacements could be registered and printed by an automatic data acquisition system.
After the bolt elongations had been measured the average calibration curve for bolts from the same batch and with the same grip was used to convert the elongation readings into bolt forces. All test specimens have been loaded till failure.



Lineair displacement transduces placed at various parts of the test specimen.

6. Test results and comparison with the theory

The test results have been reported in the table on page 15. The factor T/B_u is that part of the ultimate tensile load of the bolts with useful effect of efficiency for the purpose of supporting the applied tensile load T.
The meaning of the characters A, B or C in the last column (to signify the collapse mechanism) is the same as given in figure 8 on page 5, and in the table on page 11.

Test results					
drawing of the test specimen	plate thickness t in mm	2T in kN	2Bu in kN	T/Bu	Collapse mechanism with reference to the figure
	17	560	693	0,81	B 2 bolts broken
	20	635	673	0,94	B 3 bolts broken, 1 thread stripping
	25	656	721	0,91	B 4 bolts broken
	32	658	679	0,97	A 3 bolts broken, 1 thread stripping
	17	595	693	0,86	B see figure 25 1 bolt broken, 1 thread stripping
	20	653	688	0,95	B see figure 26, 3 bolts broken, 1 thread stripping
	25	650	672	0,97	B see figure 27. 1 bolt broken, 1 thread stripping
	32	679	766	0,88	B see figure 28. 3 bolts broken, 1 thread stripping
	20	680	775	0,88	B see figure 29. 3 bolts broken, 1 thread stripping
	25	709	738	0,96	B see figure 30. 4 bolts broken
	32	660	692	0,95	B see figure 31. 1 thread stripping, 1 bolt broken

The theory which has been developed in chapter 2 for T-stub flanges needs some completion in order to compare these results with the theoretical ones.

The formulas (1a) and (2a) can be applied directly for the connections at which the planes having the tensile forces are in alignment.

The plane of symmetry a-a can be considered as being rigid. However, the situation for the bolts is not the same as with a rigid base because the bolts must now follow the deflections of two flange plates. Nevertheless the theory is directly applicable. However, it cannot be applied to the connections in which the planes with the tensile forces are perpendicular to each other (figure 13 and 14 on page 28 and 29). The deflections which such a test specimen have to endure have been drawn in figure 18 on page 30. However, the train of thought stated hereafter includes the possibility of using the formulas (1a) and (2a).

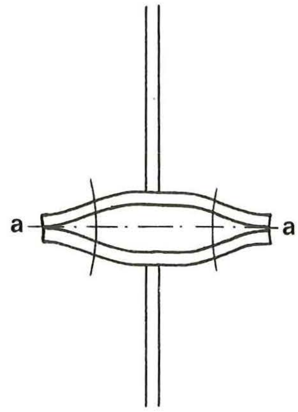


figure 17

Two separated prying forces, Q_1 (T-stub flange) and Q_2(column flange), do not develop in this type of connection (figure 18 on page 30 show that the deflections prohibit this) but a system of two symmetrical forces $\frac{1}{2}$ Q, does develop, for example, at the localities as given in figure 20 and 21.

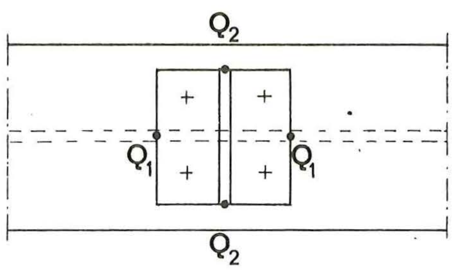


figure 19

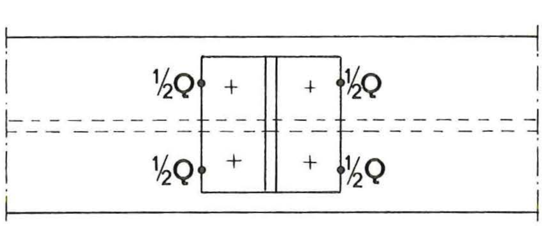


figure 20

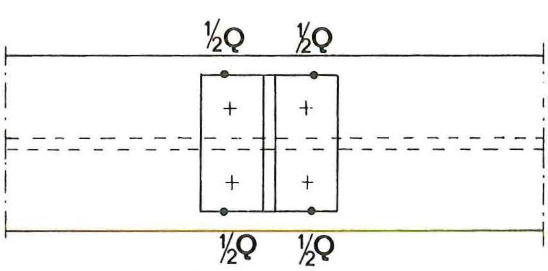


figure 21

The situation shown in figure 20 will occur if the T-stub flange is weaker than the column flange, while the situation according to figure 21 will occur if the T-stub flange is stiffer than the column flange.

The optimum situation developes when the T-stub flange has the same rigidity as the column flange. Then the forces, $\frac{1}{2}$ Q, develop at the corners of the T-stub flange (see figure 22)

This means that the T-stub flange as well as the column flange has the following force distribution:

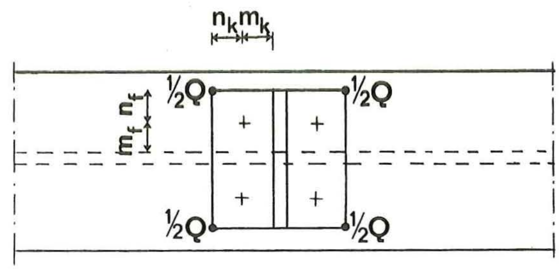
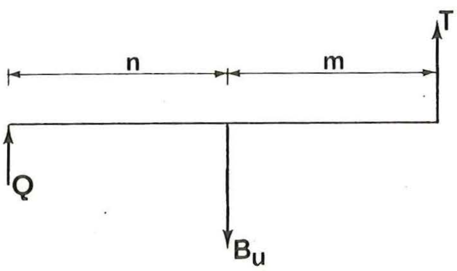


figure 22



The following normal formulas are applicable for both flange plates.

(1a) $T \times m - (B_u - T)n \leqslant 4/3\ M_v'$

$T \times m \leqslant 4/3\ (M_v' + M_v)$

$B_u - T \geqslant 0$

ultimate limit state loadfactor 2 (rupture of the bolt)

Assume that with the above-mentioned formulas the computation concerning the T-stub flange gives a higher value for T than the computation with the column flange. In this case the column flange is the determining factor.

At the moment that the column flange reaches its optimum situation (failure at the highest reachable, T,) the situation for the T-stub flange will not yet have reached its optimum. This means that the forces, $\frac{1}{2}$ Q, given by the computation of the column flange are not in the optimum position (see figure 21) and/or the stress in the T-stub flange has not yet reached the maximum value as will be evident from the following.

The T-stub flange is subjected to a smaller force,T, than computed.

The optimum situation has been assumed for computation of the T-stub flange with:

(1a) $T \times m - (B_u - T)\ n = 4/3\ M_v$

or (2a) $T \times m = 4/3\ (M_v + M_v')$

Assume that formula (1a) has been the determining one (collapse mechanism B).

Then, mathematically speaking with in accordance a smaller T in formula (1a): n has to be smaller ($n' < n$) to keep the right-hand side of the equation ($4/3\ M_v$) constant and/or: the right-hand side has to be less than $4/3\ M_v$. Consequently, the stress must be decreased. The optimum design situation for the T-stub flange has been drawn in the following figure.

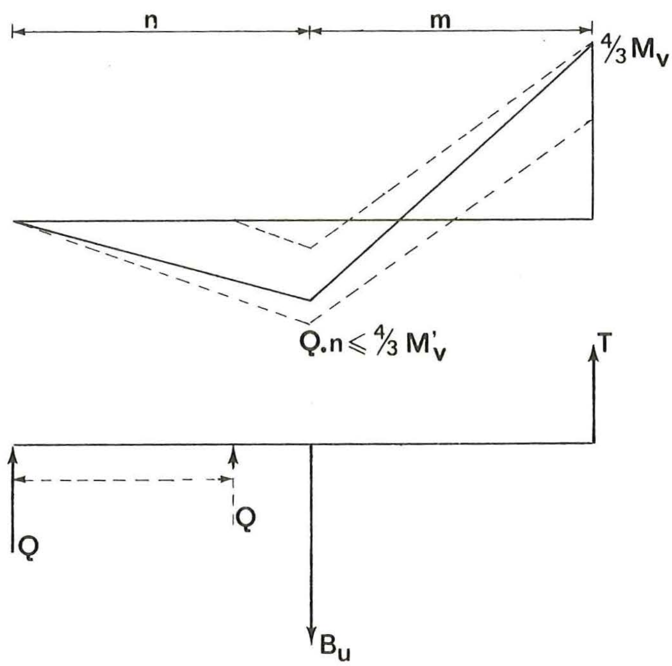


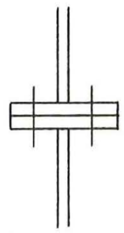
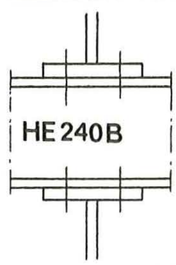
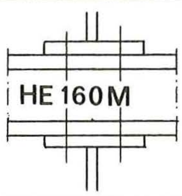
figure 23

Possible moment lines corresponding to smaller values of T resulting from failure of the column flange are shown as dotted lines.
An example of computation has been given in Appendix A in example (5).
This train of thought is not important for the computation because it is assumed that the situation occurring in the T-stub flange will never be more unfavourable for bolt or plate than the optimum computed one would be.
In other words, the construction adapts it self to the situation, and is in danger only if the lowest of the loads, T, as computed in the optimum state is exceeded. T-stub flange and column flange can be computed separately with the formulas (1a) and (2a) on the grounds of this train of thought after which the smallest value for the load T given by this computation has to be accepted. Three data for determining the theoretical T failure of the test specimens are, however, still missing:
a) The real yield-stress, σ_v, of all flanges. These stresses have been determined and reported in the following table.

	yield stress in N/mm^2	ultimate stress in N/mm^2
T-stub flange with t = 17 mm	357	519
T-stub flange with t = 20 mm	364	535
T-stub flange with t = 25 mm	282	420
T-stub flange with t = 32 mm	272	407
HEB 240 flange	300	464
HEB 160 flange	270	435

b) The real ultimate tensile load of the bolt. Where possible bolts from one manufacturing process have been used. As described in the test procedure (chapter 5) 4 bolts of every batch have been tested.
The test results have been reported in the following table.

All bolts failed in the threaded part unless otherw ise indicated.

drawing of the test specimen for which the bolts are intended	thickness of the T-stub flange	the grip of the bolt	ultimate load of 4 bolts in kN all bolts M 16 quality 10.9				the average in kN
	17	38	172,5*	173,8	174	172,5*	173,2
	20	44	167,5	168,6	166,8	169,6*	168,1
	25	54	184**	170	189	177,5**	180,1
	32	68	165,2	171,3	169,5	172,5	169,6
	17	38	172,5*	173,8	174	172,5*	173,2
	20	41	171,8	171,3	171,3	173,8*	172,1
	25	46	167,5	167,3	169	168,5	168,1
	32	53	191,6	192,8	193	188,6	191,5
	20	47	197,6	190,7	192,5	193,5	193,6
	25	52	184	186,8	180,4	186,8	184,5
	32	59	174		171	175	173

* thread stripping of the bolt

** thread stripping of the nut

For the load-elongation curve of the bolts see pp 59 through 68.

c) The effective length (yielding length) of the column flange by means of which computations have to be carried out.

$\ell\sqrt{2} + a$ has been assumed for the effective length.

In this formula, a, is the bolt pitch ,

and , ℓ, the length of the flange as given in the following figure.

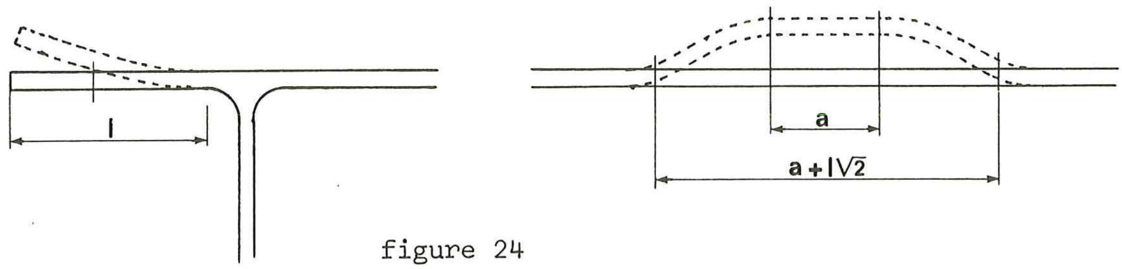


figure 24

This effective (yielding) length has been determined by observing the behaviour of the column flanges connected with 32 mm T-stub flanges.
The behaviour of these T-stub flanges is such that infinite rigidity can be assumed for the computation as well as for the test.
Likewise, the plastic deflections of the test specimens have been checked. (see figure 25-32 on pp 31 through 37) The yielding length computed with the above-mentioned formula is 213 mm forHEB 240 and 166 mm for HEM 160.
In the following figures the effective (yielding) length has been drawn to give an impression of the proportions.
The scale is 1:5.

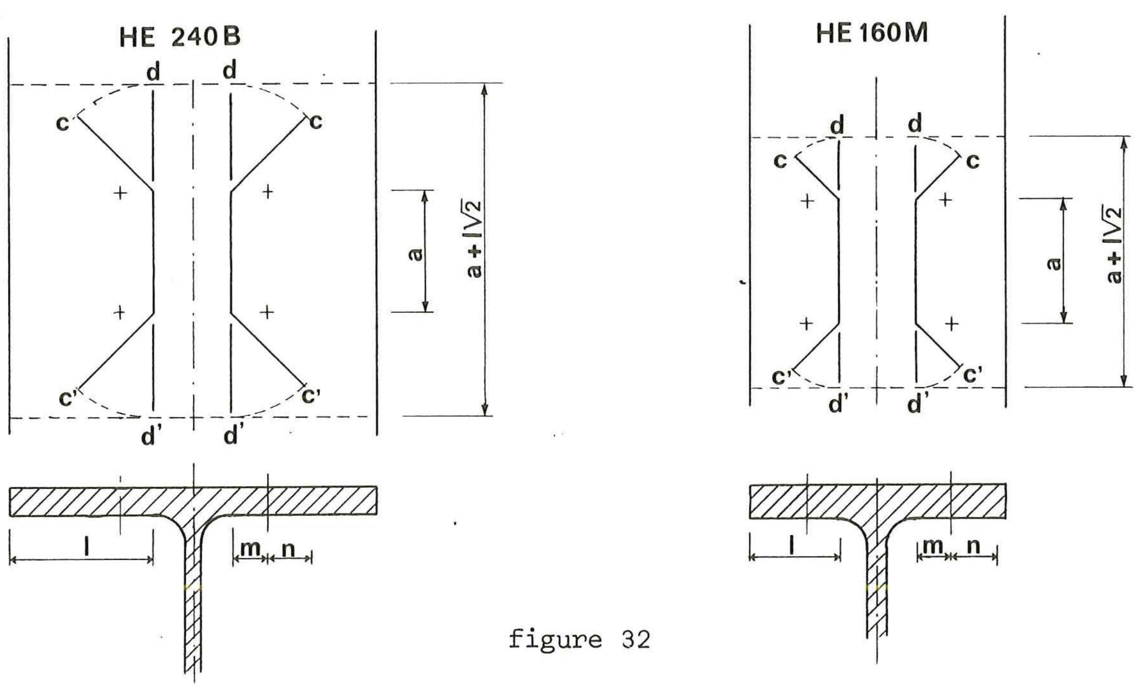
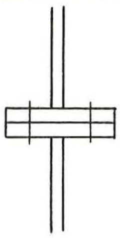
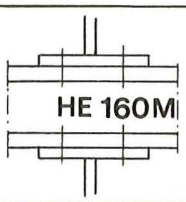
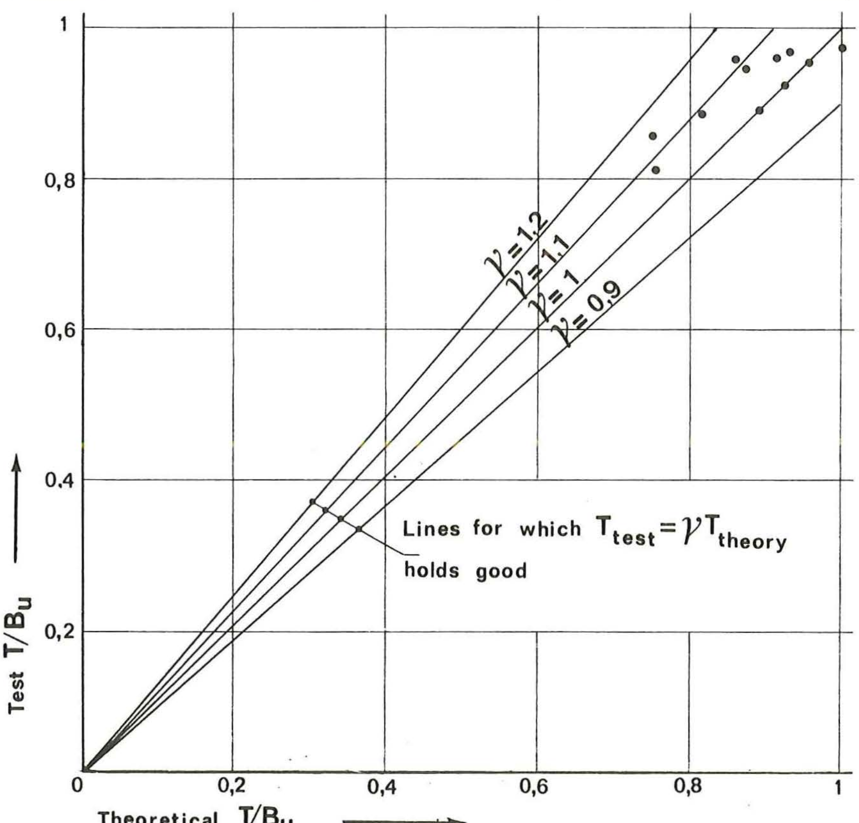


figure 32

The assumption has been made that there is plastic deformation of the section over the lines c-c'; this has been changed in the lines d-d' for the computation. In the next table the test results have been compared with the theoretically determined values corresponding to the above-mentioned method of computation.

	Test results					Computation		
test specimen	T-stub flange thick-ness t	2T in kN	$2B_u$ in kN	T/B_u	Collapse mechanism	2T in kN	T/B_u	Collapse mechanism
	17	560	692,8	0,81	B	518	0,75	B
	20	635	672,5	0,94	B	580	0,86	B
	25	656	720,5	0,91	B	652	0,91	B
	32	658	678,5	0,97	A	678,5	1,00	A
	17	595	692,8	0,86	B	518	0,75	B/T-stub flange
	20	653	688,2	0,95	B	588	0,85	B/T-stub flange
	25	650	672,3	0,97	B	626	0,93	B/column flange
	32	679	766	0,88	B	680	0,88	B/column flange
	20	680	774,3	0,88	B	630	0,81	B/T-stub flange
	25	709	738	0,96	B	662	0,91	B/T-sub flange
	32	660	692	0,95	B	656	0,95	B/column flange



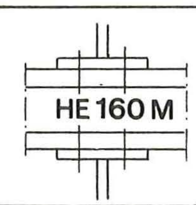
The results reported above have been plotted in the adjacent graph.

In the graph $\frac{T_{test}}{T_{theory}} = \gamma$ (γ is an "extra safety") It means that for $\gamma = 1$

the test is in complete agreement with the theory. The test is more favourable for $\gamma>1$, and less favourable for $\gamma<1$. In the computation, the average of yield stress and ultimate bolt force, B_u,has been used. Slight deviations from the theory may be caused by deviations from, σ_v, or ,B_u,
The development of the bolt force resulting from theexternal applied load has been plotted in the graphs 34 through 44 on pp 38 through 48.

The deformations measured during the test have been plotted in the graphs 45 through 54 on pp 49 through 58.

These graphs provide no further information for the computation: the deflections have been measured mainly in the elastic state, while the computation assumes the plastic state.
It is clear that the deformations remain small in the serviceability limit state which is still elastic as will be obvious from the following table.
In this table the connection is subjected to an applied load of 2T = 320 kN.
This gives an external applied load of $\frac{320}{4}$ = 80 kN for one bolt. The allowable bolt tensile force according to Dutch Standards is 79 kN.
Taking into account the prying force, Q, the allowable load, 2 $\overline{T}$, will certainly be lower than 320 kN.

drawing of the test specimen	flange plate thickness t	Deformations as plotted in graphs 49 through 54 at an applied load/bolt of 80 kN	
		measuring points $\frac{\Sigma 9,10}{4}$ in mm	measuring points $\frac{\Sigma 1,2,3,4}{4}$ in mm
	17	not measured	not measured
	20	0,385	0,270
	25	0,320	0,225
	32	0,240	0,140
	20	0,280	0,265
	25	0,245	0,210
	32	0,225	0,180

The measuring points, $\frac{9 + 10}{4}$, is the deformation which has been composed of:

1^o the deflection of the T-stub flange and the elongation of the tensile strip over a length of about 50 mm.

2^o the elongation of the bolts.

3^o the deflection of the column flange and the half of the elongation of the elongation of the column web.

The measuring points, $\frac{1,2,3,4}{4}$, is the deformation which has been composed of:

1^o the deflection of the T-stub flange and the elongation of the tensile strip over a length of about 50 mm.

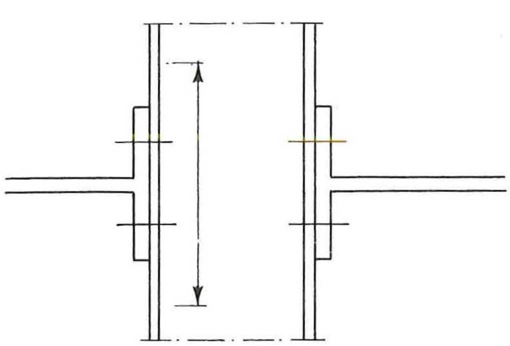
2^o the elongation of the bolts.

3^o the deflection of the column flange.
The difference in measurements reported above gives the elongation of half of the column web. This gives an average of 0,10 and 0,03 mm, for HEB 240 and HEM 160 respectively.

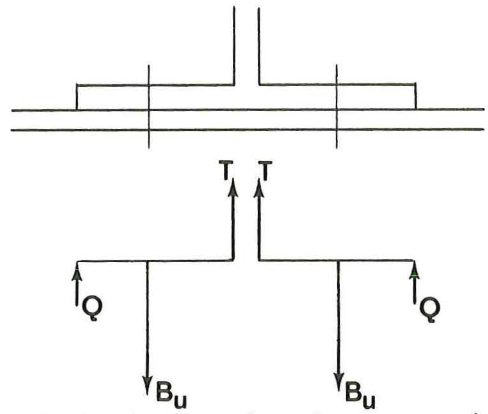
Depending on the grip the bolt elongation is 0,01 - 0,03 mm at the applied load of 80 kN/bolt.

7. Concluding remarks

The theory developed in the Stevin-report 6-69-13 and presented in a modified form in this report appears applicable as well to the T-stub connected with a relatively weak support such as column flanges.
The column flanges may be computed as a T-stub on the understanding that one assumes an imaginary effective (yielding) length. A slight difference between the computed values and the test results occur if one takes into account the strain hardening of the material of T-stub flange and



column flange by applying a factor 4/3 M_v in the ultimate limit state.
If, when calculating the design, the design load (in this case: failure load)is obtained by multiplying the characteristic load by a load factor, 2, it would be advisable to use the following formulas:



$T \times m - (B_u - T)n \leq 4/3\ M_v$ (1a)

$T \times m \leq 4/3\ (M_v + M_v')$ (2a)

$B_u - T \geq 0$

B_u = the total ultimate tensile load of the bolts fitted at one side of the tensile strip.

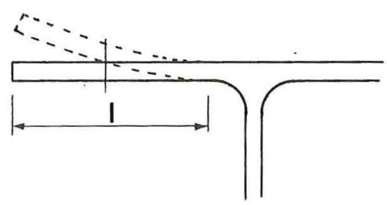
T = half of the tension force applied to the the connection.

Q = the prying force between T-stub flange and column flange. It is assumed that this force acts on the edges of the T-stub flange.

M_v = the plastic moment next to the tensile strip.

M_v' = the plastic moment at the bolt line.

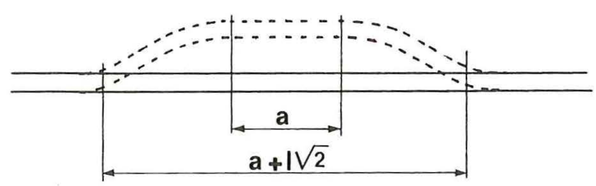
If one computes with a load factor 1.5 and thus considers the <u>limit state of great deformations</u> (yielding), the above mentioned formulas change into: (so in this case the design load is the load at which the yield force in the bolt and/or the plastic moments in the plate are reached. This design load is obtained by multiplying the characteristic load by 1.5).



$T \times m - (3/4\ B_u - T)n \leq M_v$ (1b)

$(3/4\ B_u - T \geq 0)$

$T \times m \leq M_v + M_v'$ (2b)



<u>Remarks</u>: Here, $3/4\ B_u \approx 1.5\ \overline{B}$

$\overline{B}$ = the allowable tension force of the bolt, according to Dutch Standards, multiplied by the number of bolts fitted at one side of the tensile strip.

T = half of the tensile force applied to the connection.

If one computes with the serviceability limit state (so with a design load equal to the characteristic load) then the formulas change into:

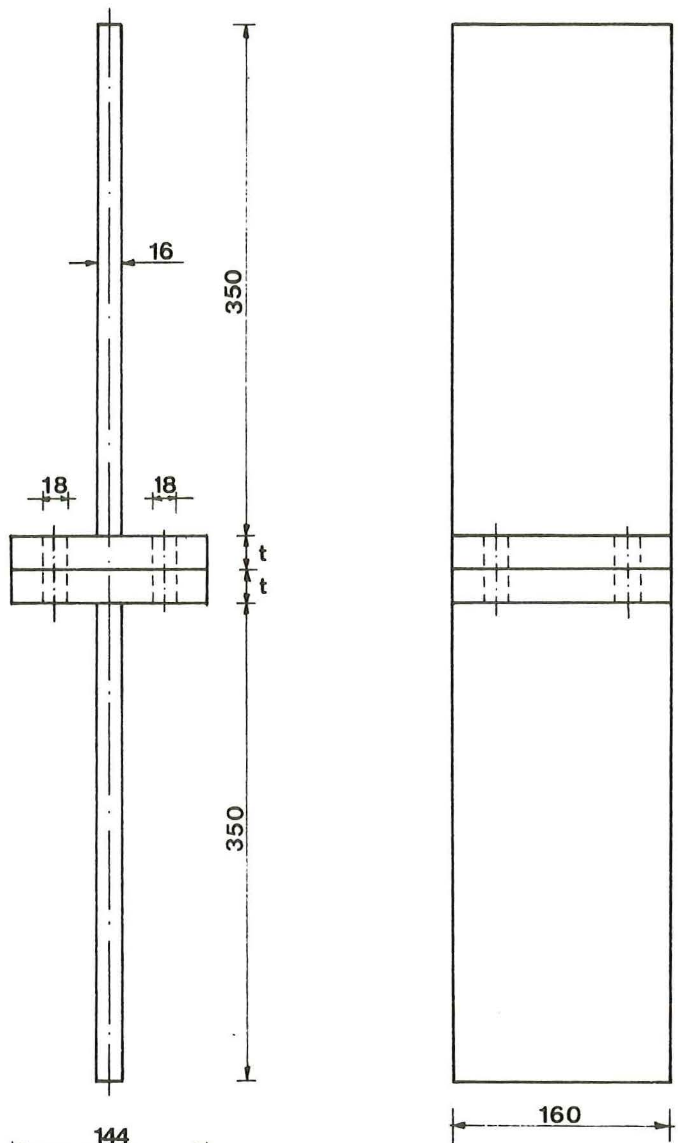
$T \times m - (\overline{B} - T)n \leq M_e$ $(\overline{B} - T \geq 0)$

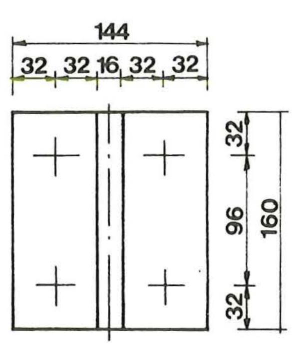
$T \times m \leq M_e + M_e'$

In these formulas, M_e is the elastic moment computed with

$\overline{\sigma} = \sigma_v$ (yield moment), so $M_e = \frac{1}{6} . b\ t^2 . \sigma_v$

An effective (yielding) length of $\ell\sqrt{2} + a$ is assumed (for the present) for a column flange. In this formula, ,a, is the bolt pitch and ,ℓ, the length of the flange outside the centre of the web fillet.
The correctness of this assumption has not yet been proved completely but it appears to give reasonable results for the tests carried out.





1 testspecimen with t= 17mm.

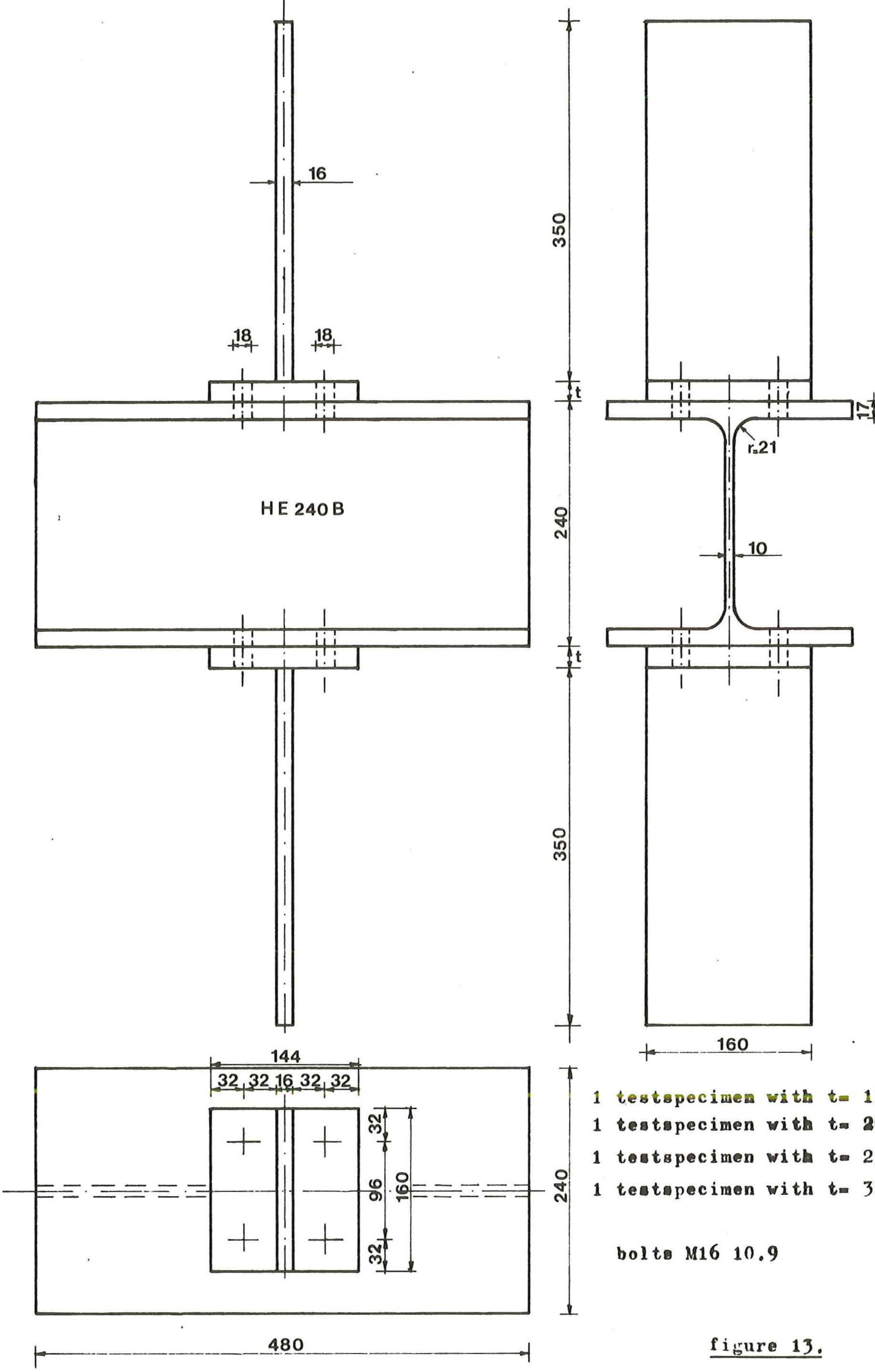
1 testspecimen with t= 20mm.

1 testspecimen with t= 25mm.

1 testspecimen with t= 32mm.

bolts M16 10.9

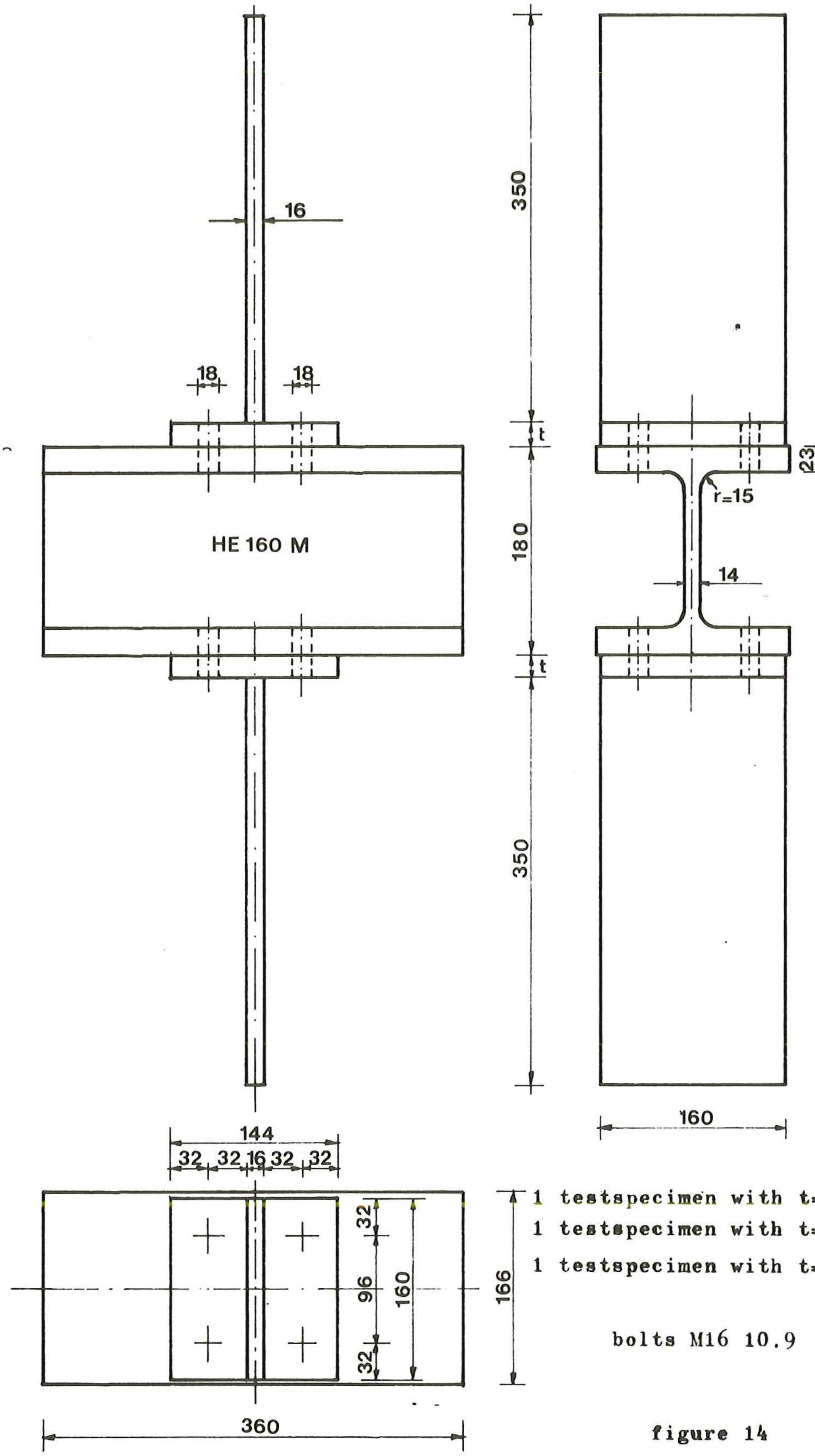
<u>figure 12.</u>



1 testspecimen with t= 17mm.
1 testspecimen with t= 20mm.
1 testspecimen with t= 25mm.
1 testspecimen with t= 32mm.

bolts M16 10.9

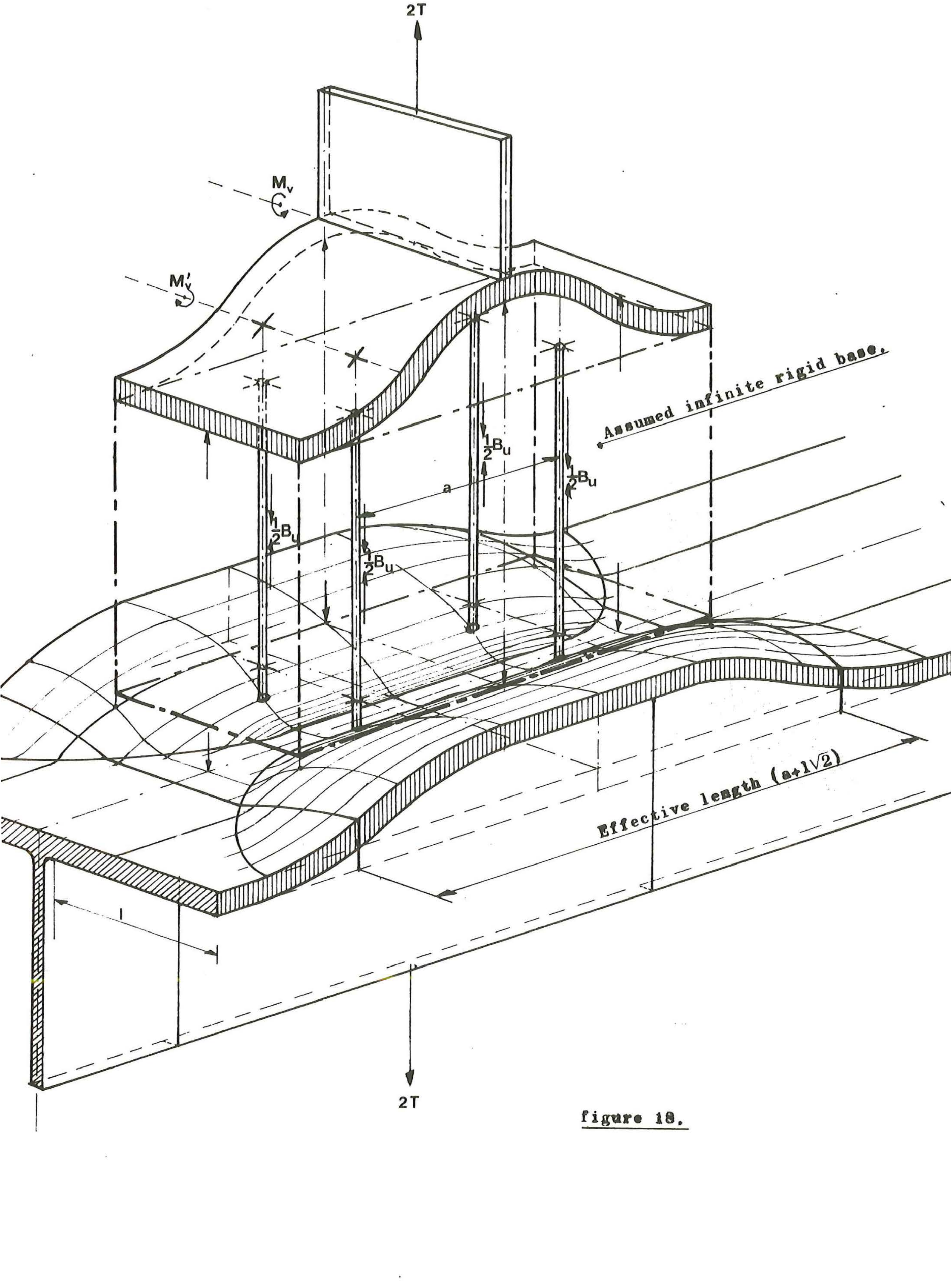
figure 13.



1 testspecimen with t= 20mm.
1 testspecimen with t= 25mm.
1 testspecimen with t= 32mm.

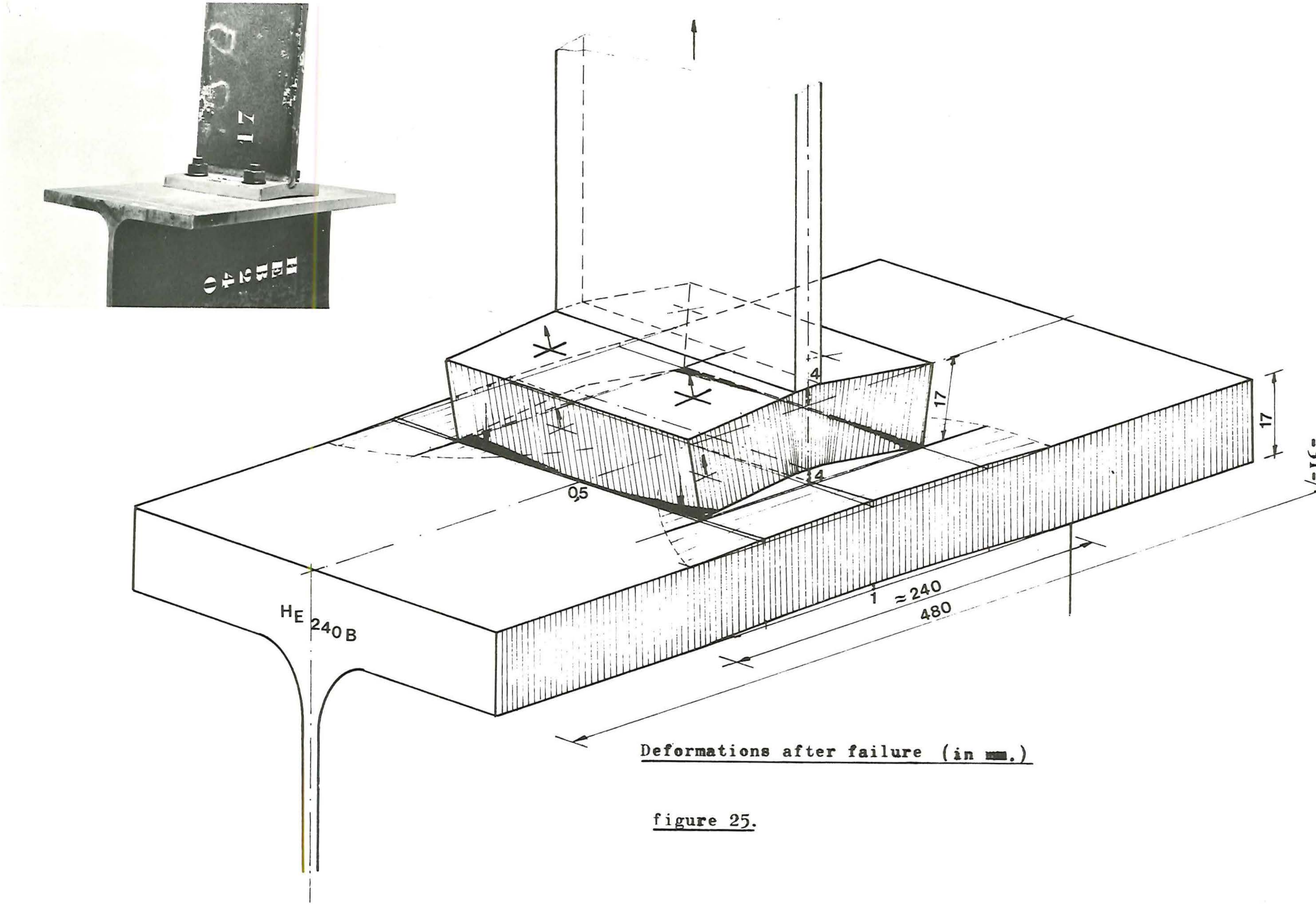
bolts M16 10.9

figure 14



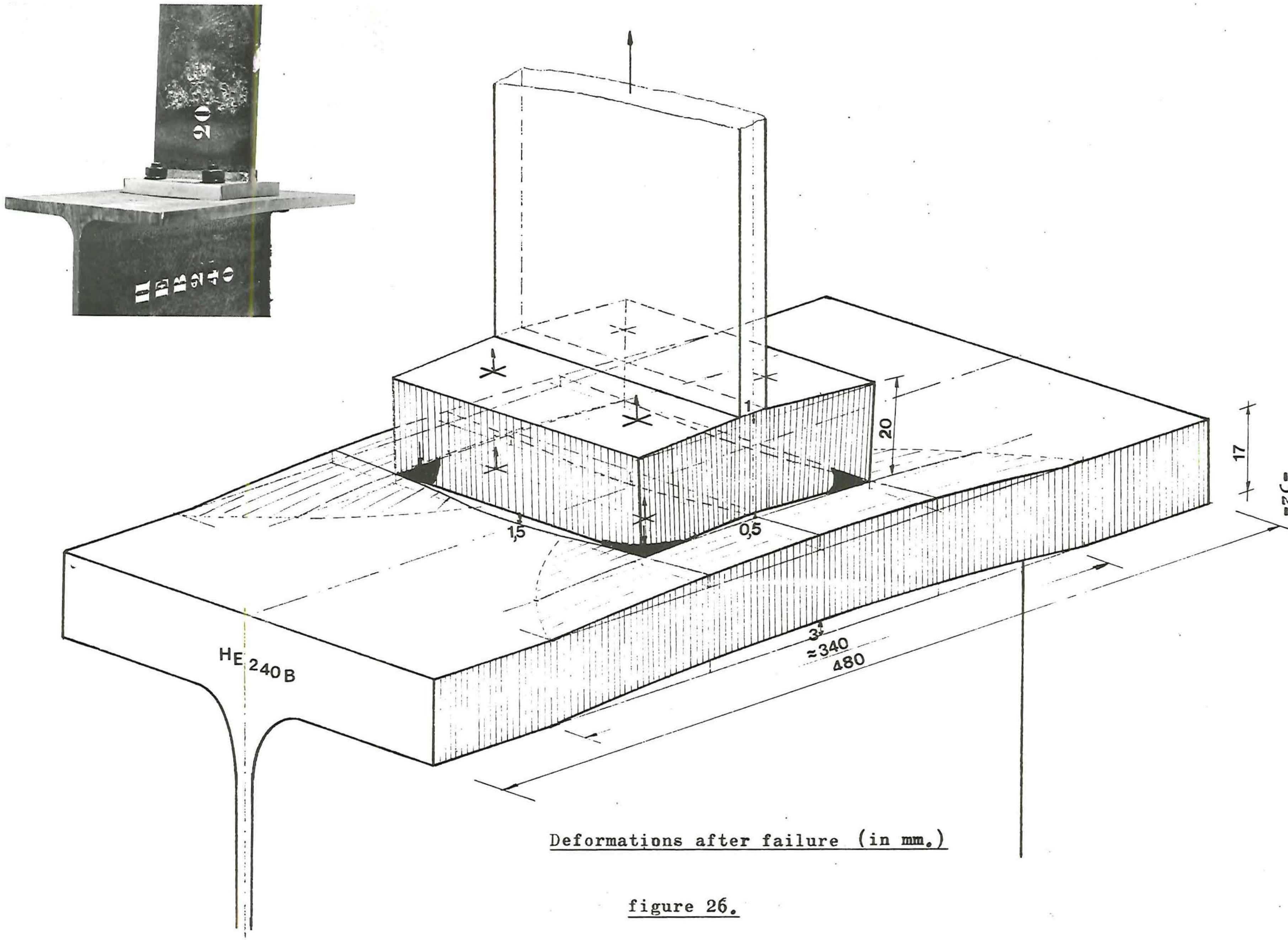
2T
M_v
M'_v
Assumed infinite rigid base.
$\frac{1}{2}B_u$
$\frac{1}{2}B_u$
a
$\frac{1}{2}B_u$
$\frac{1}{2}B_u$
Effective length $(a+l\sqrt{2})$
l
2T

figure 18.



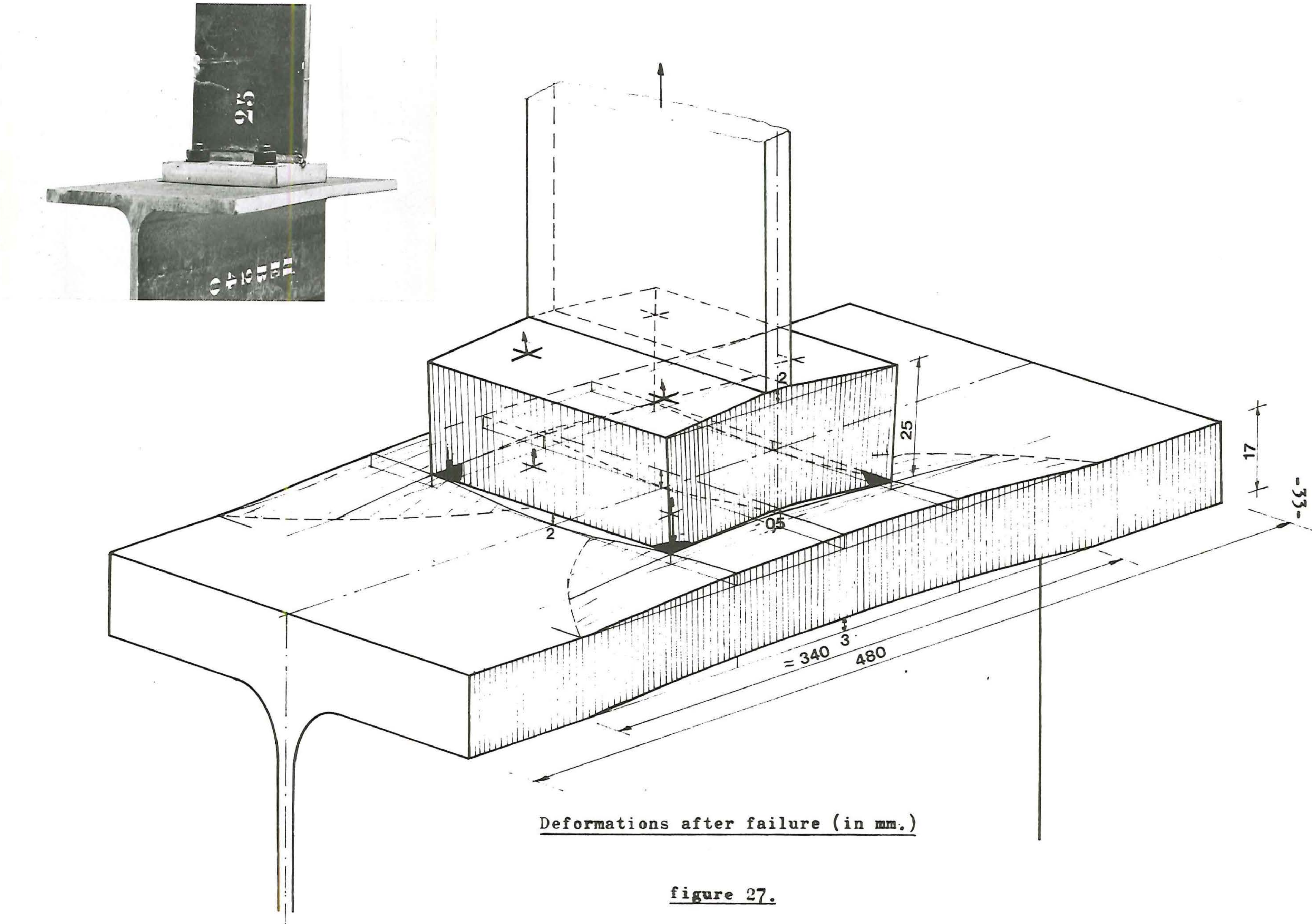
Deformations after failure (in mm.)

figure 25.



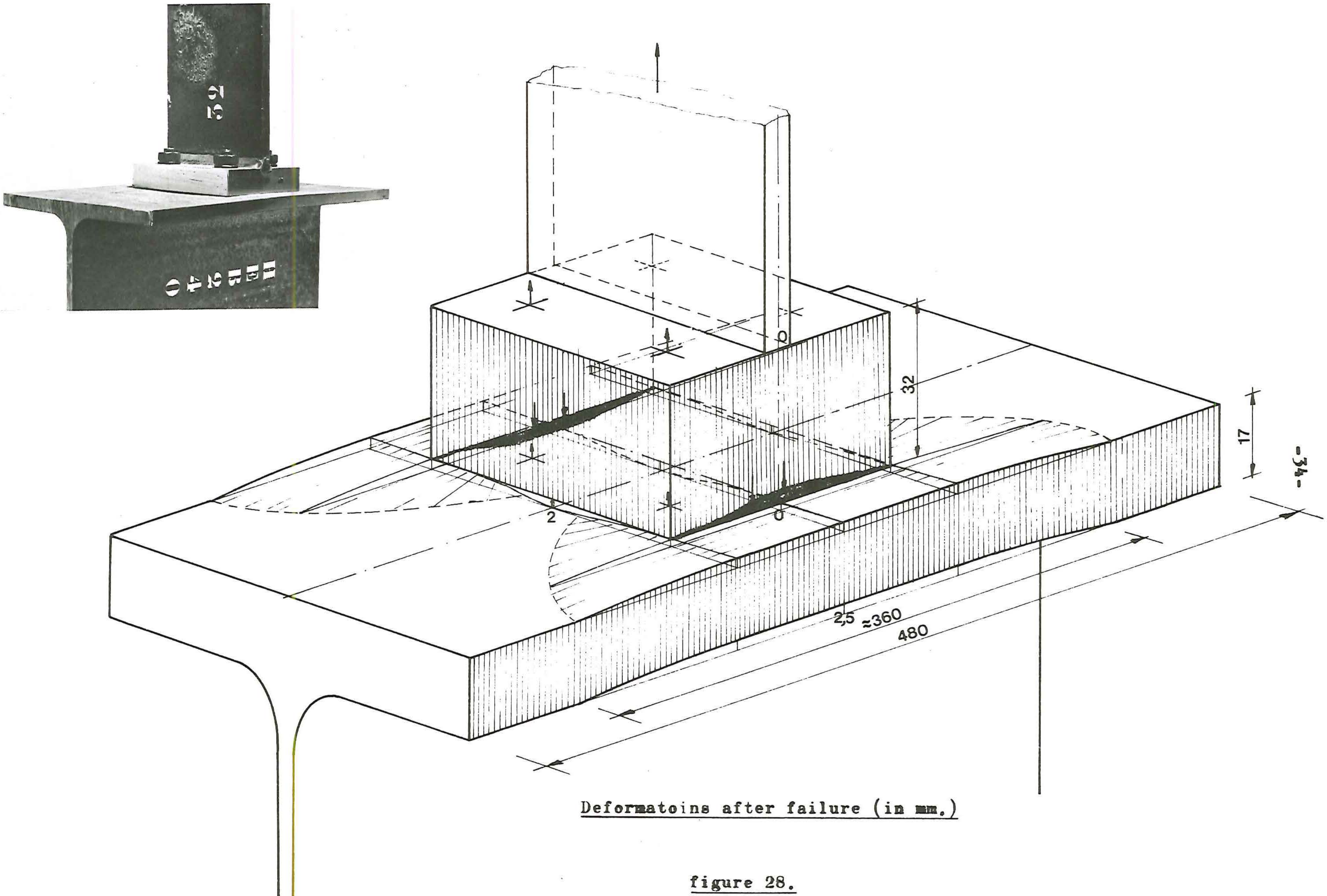
Deformations after failure (in mm.)

figure 26.



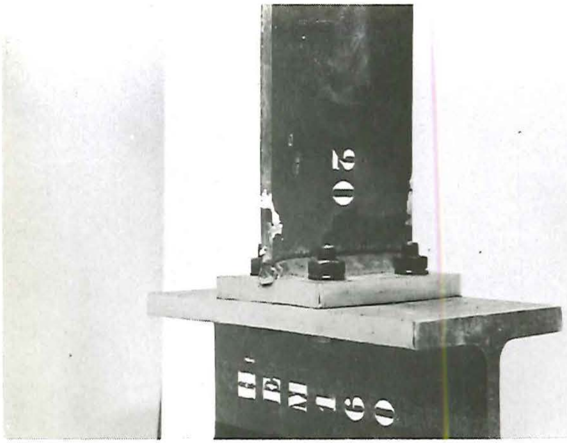
Deformations after failure (in mm.)

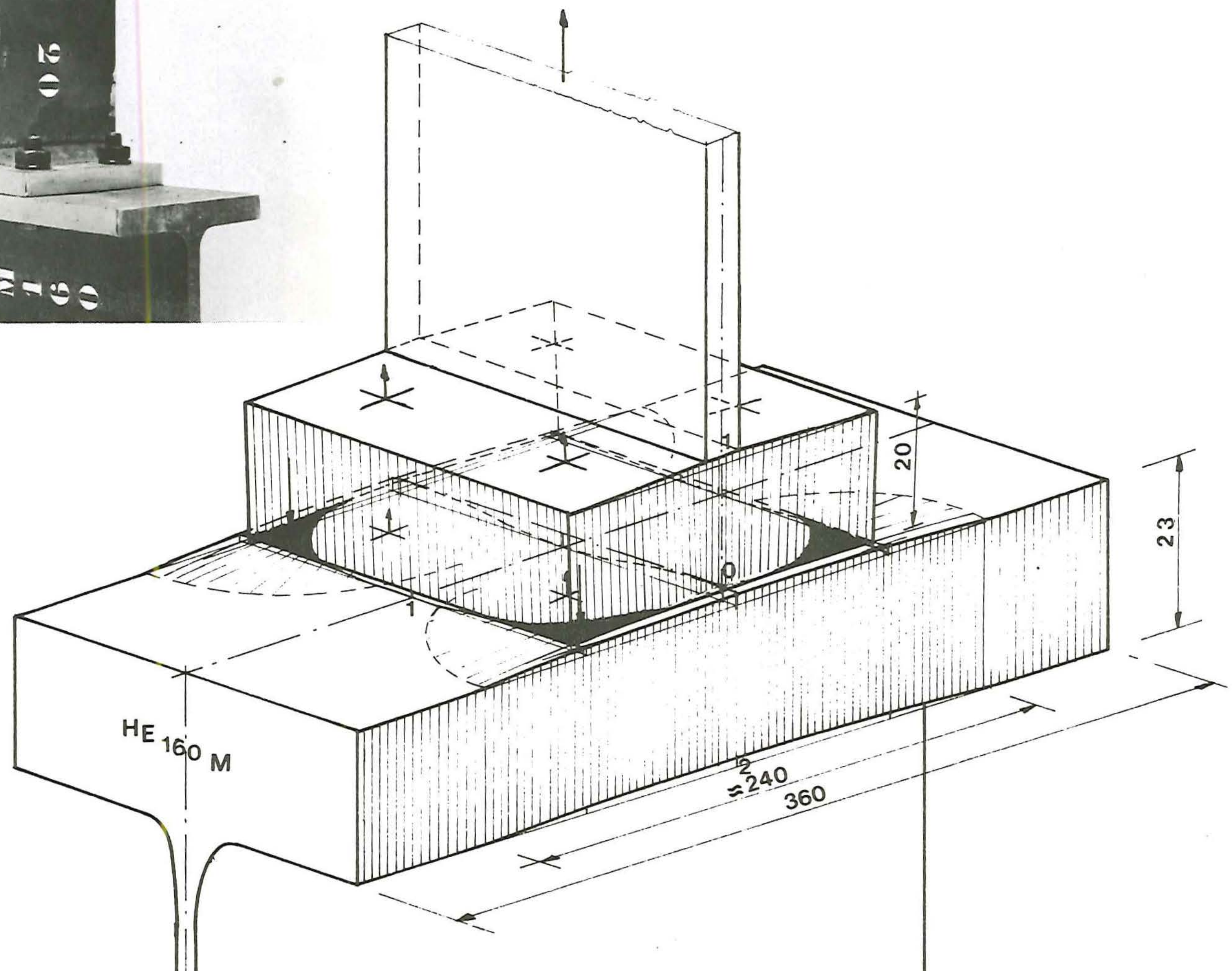
figure 27.



Deformatoins after failure (in mm.)

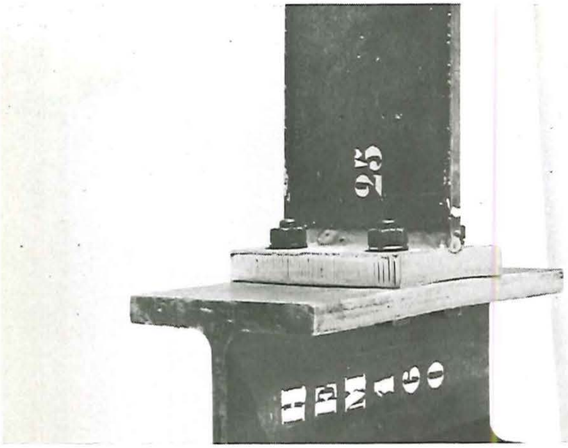
figure 28.

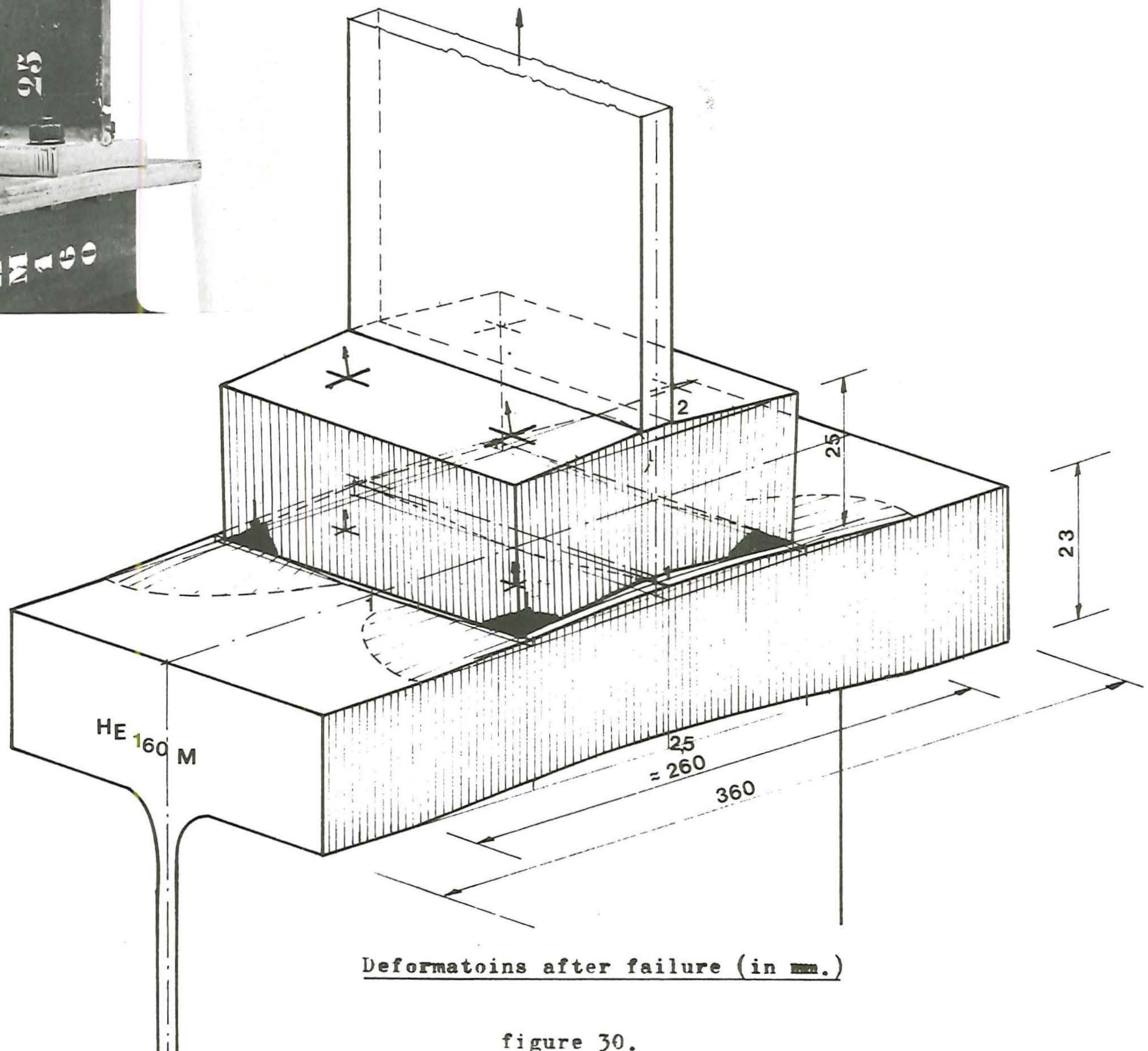




Deformatoins after failure (in mm.)

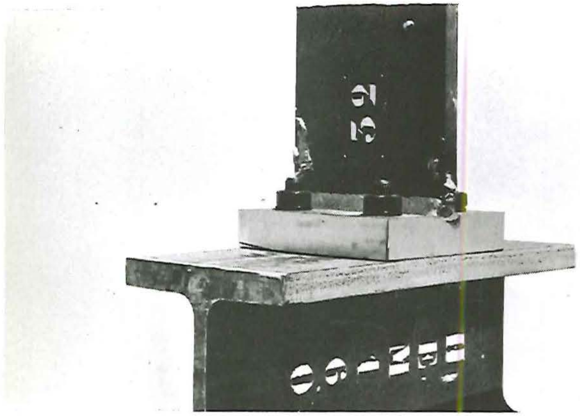
figure 29.

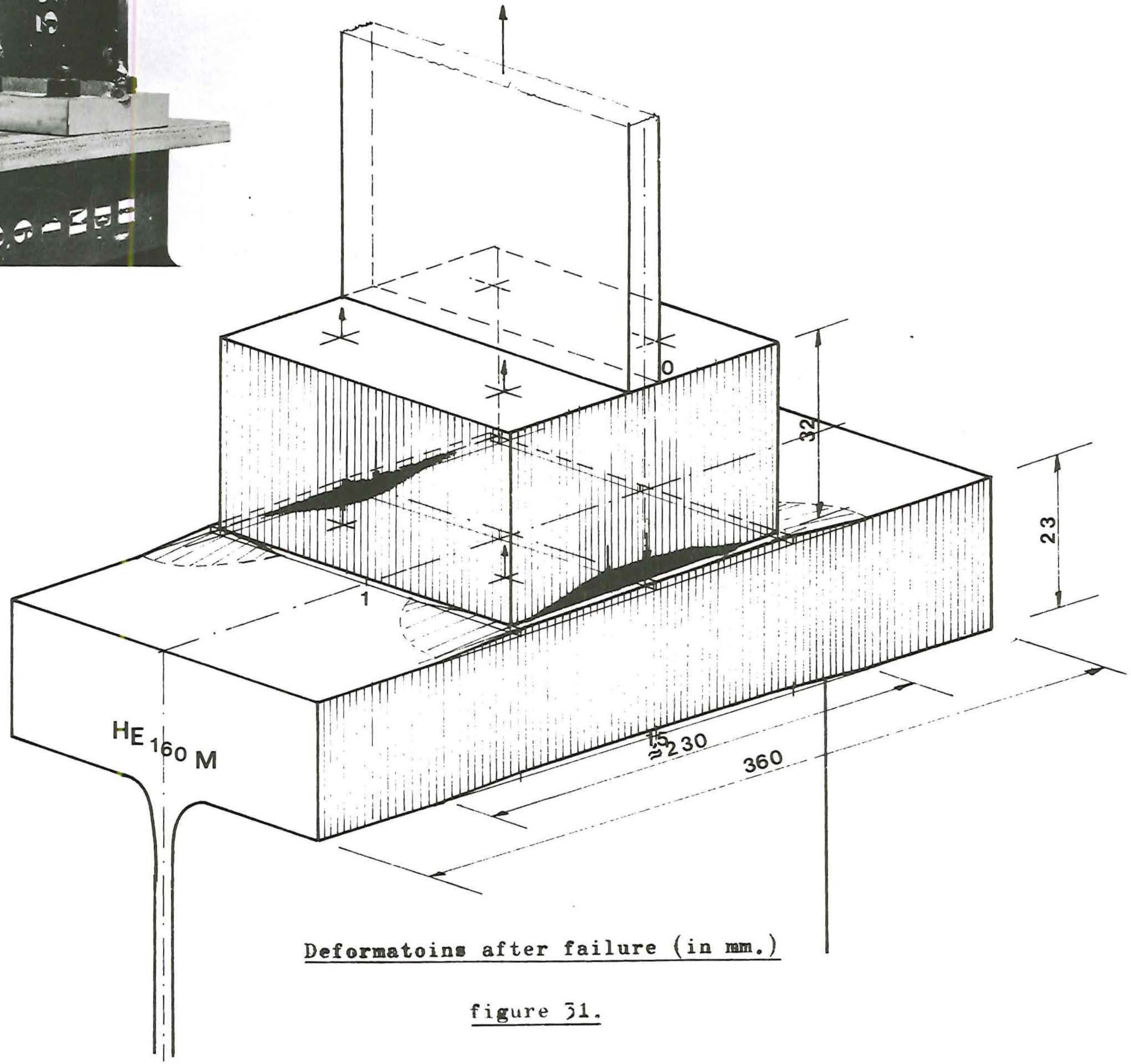




Deformatoins after failure (in mm.)

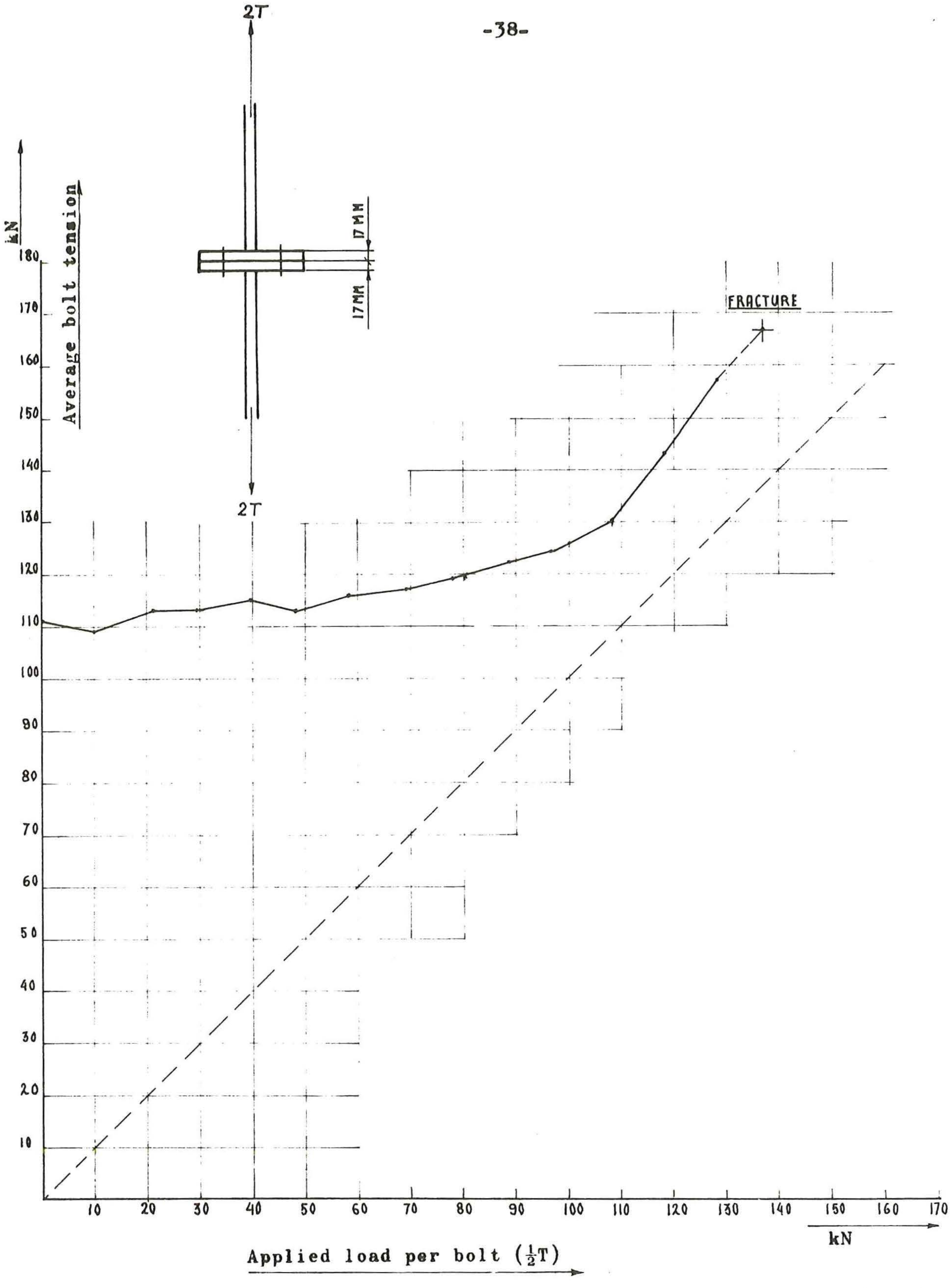
figure 30.





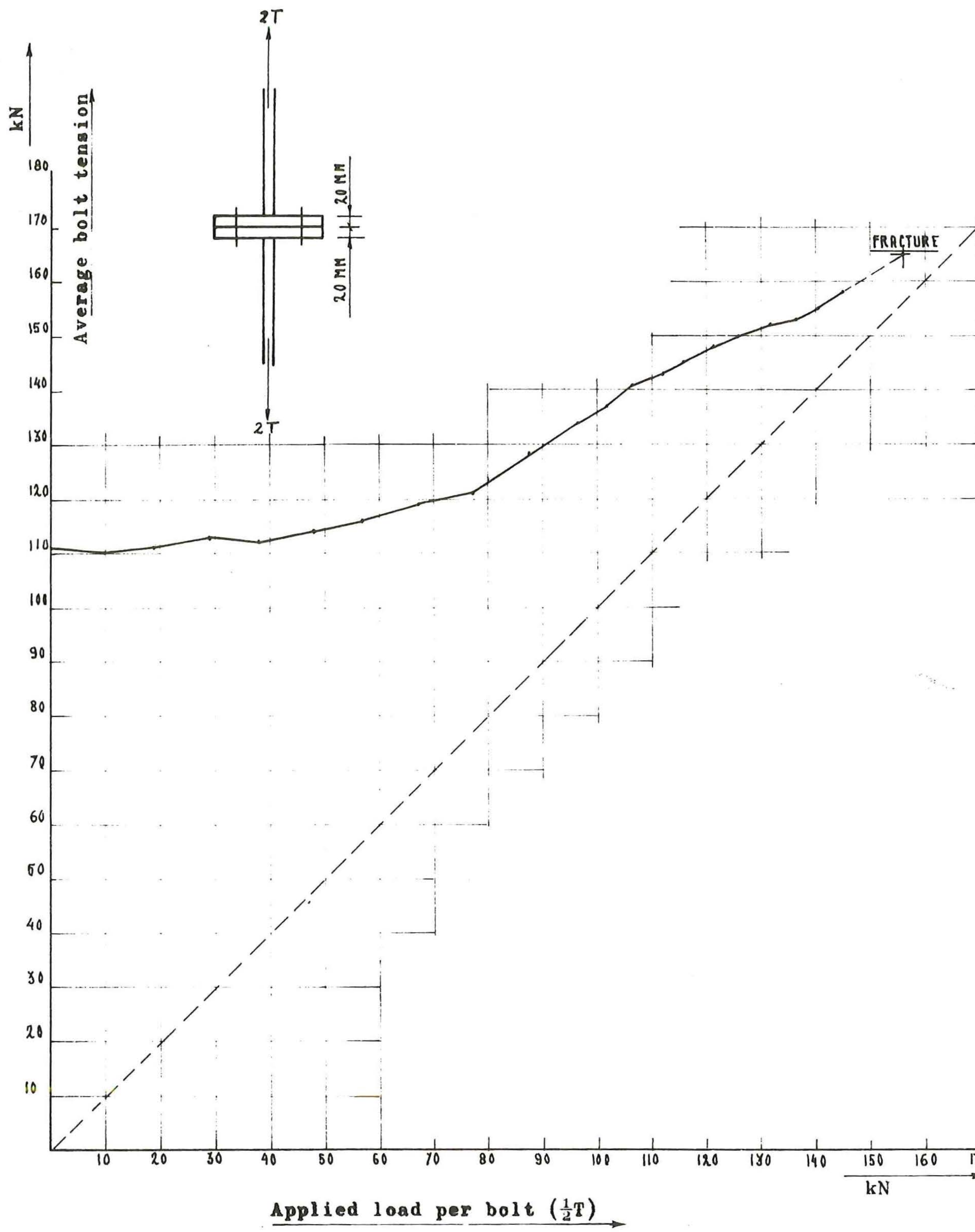
Deformatoins after failure (in mm.)

figure 31.



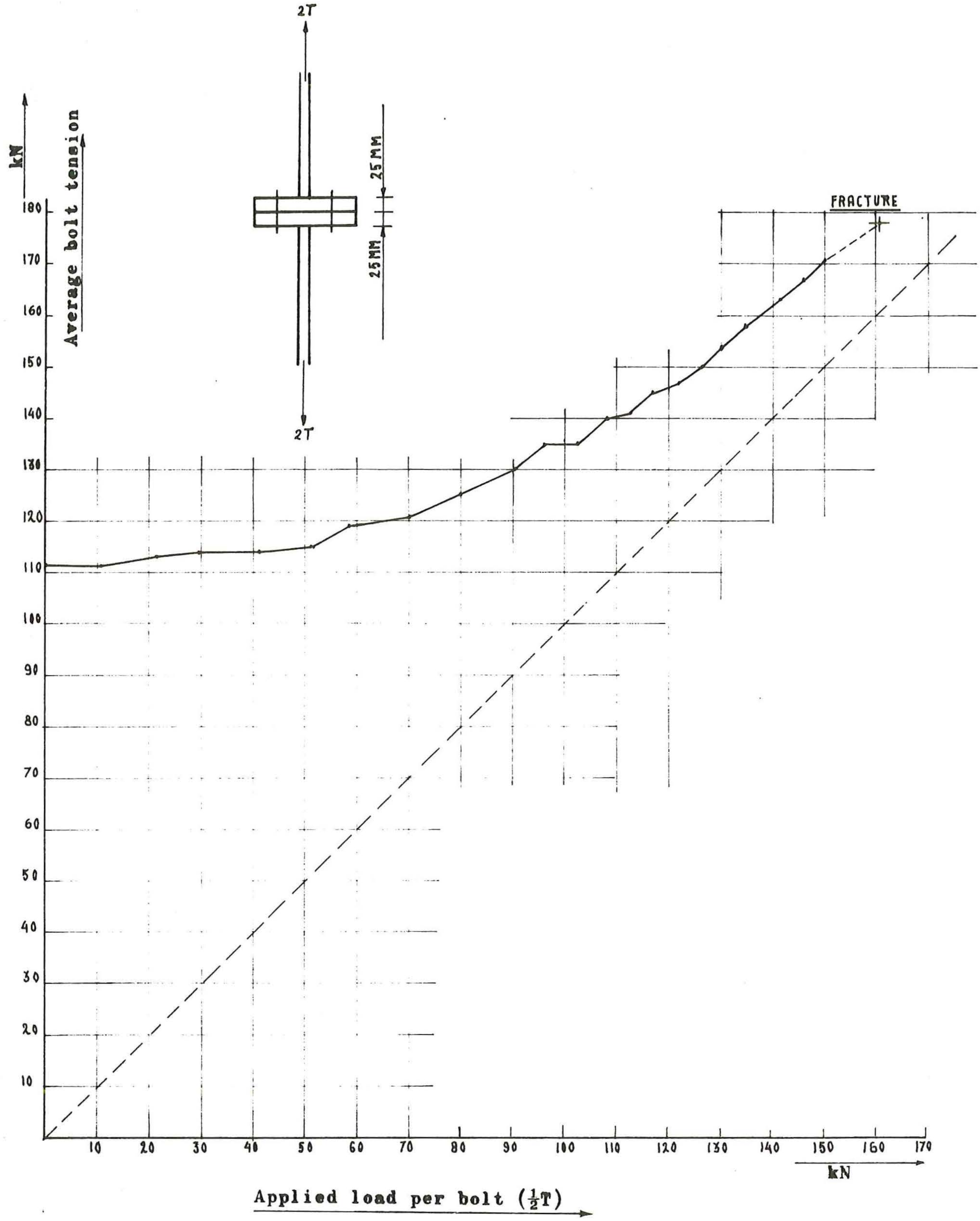
T-stub flanges 17mm

diagram 34.



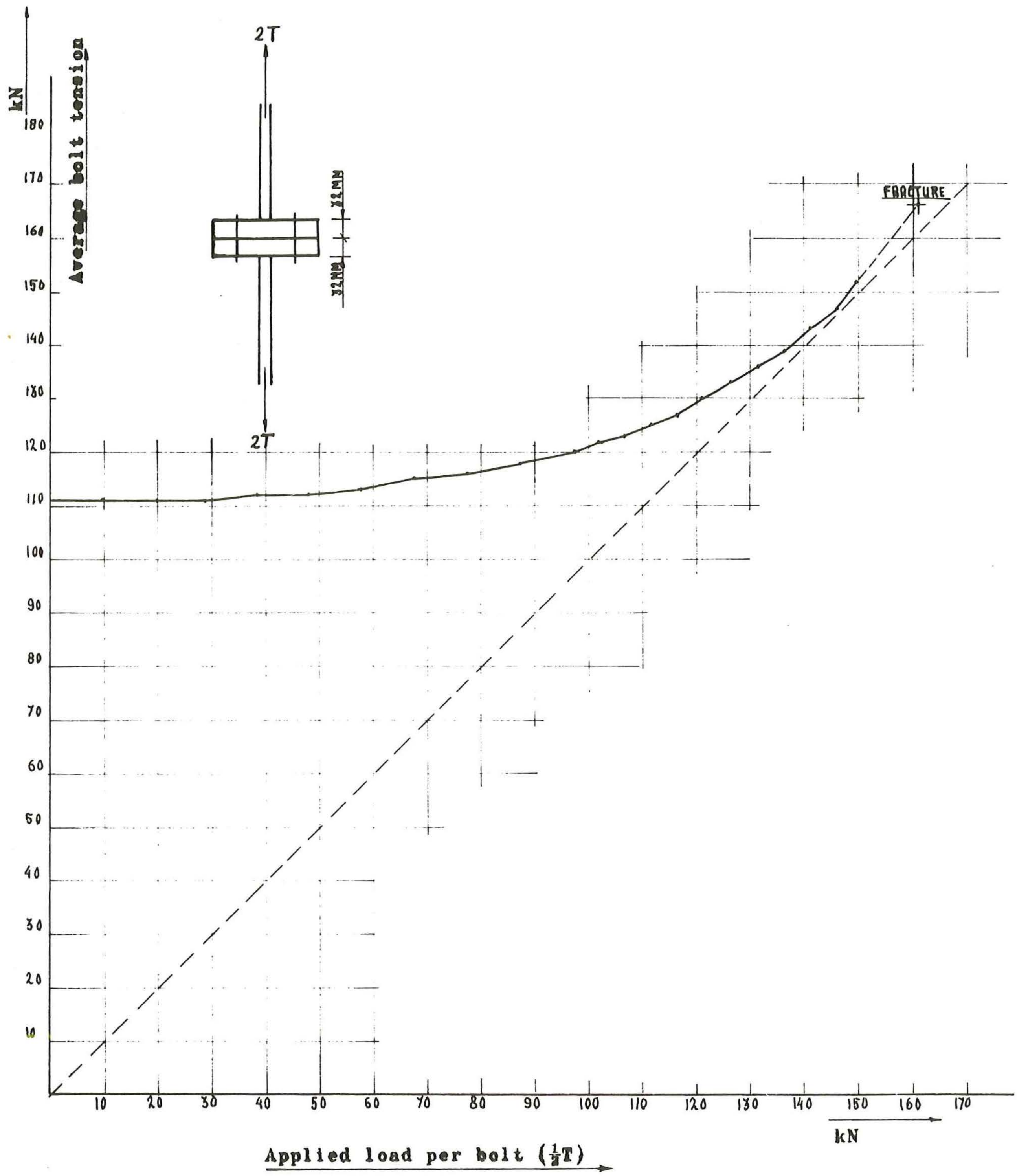
T-stub flanges 20mm

diagram 35.



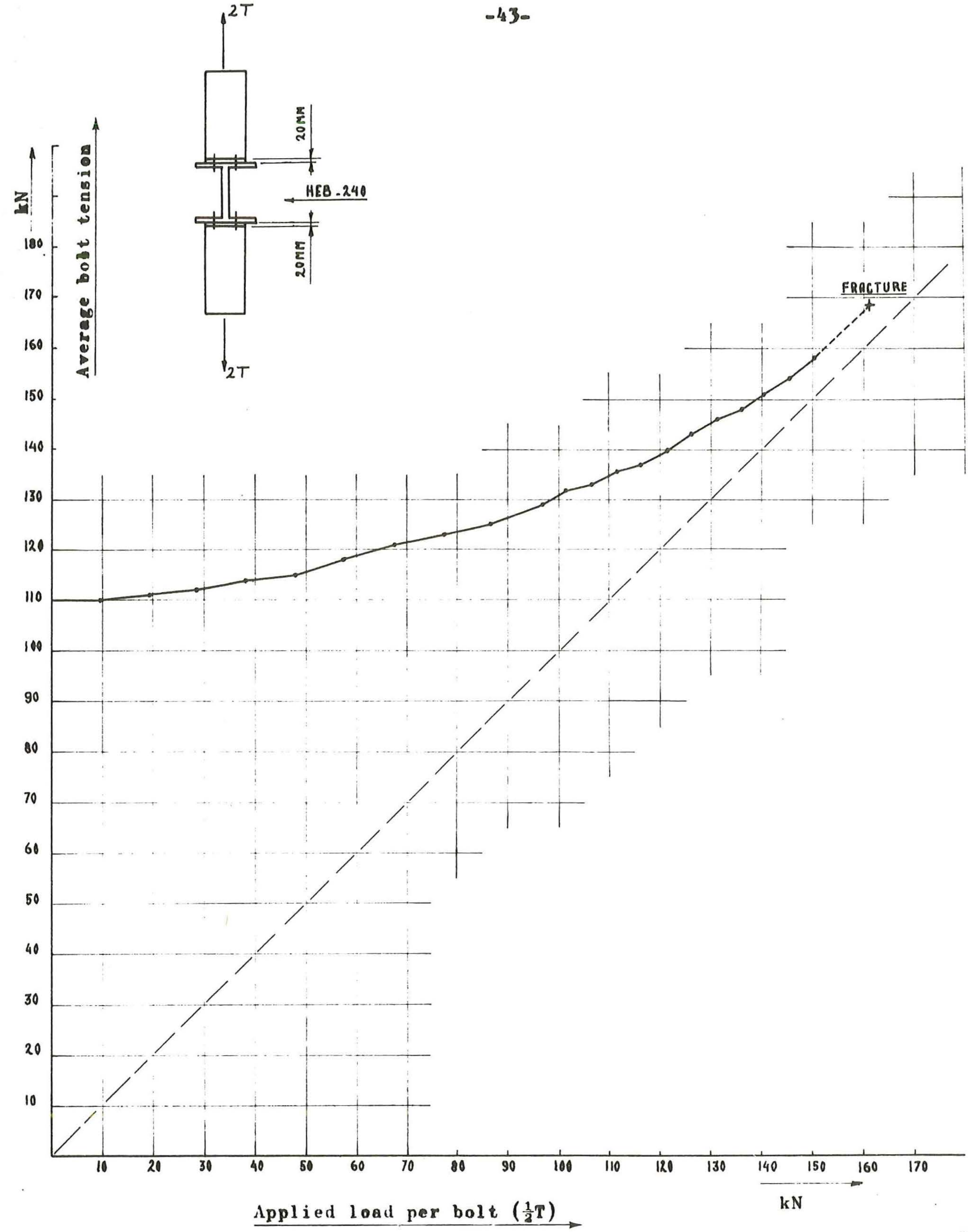
T-stub flanges 25mm

diagram 36.



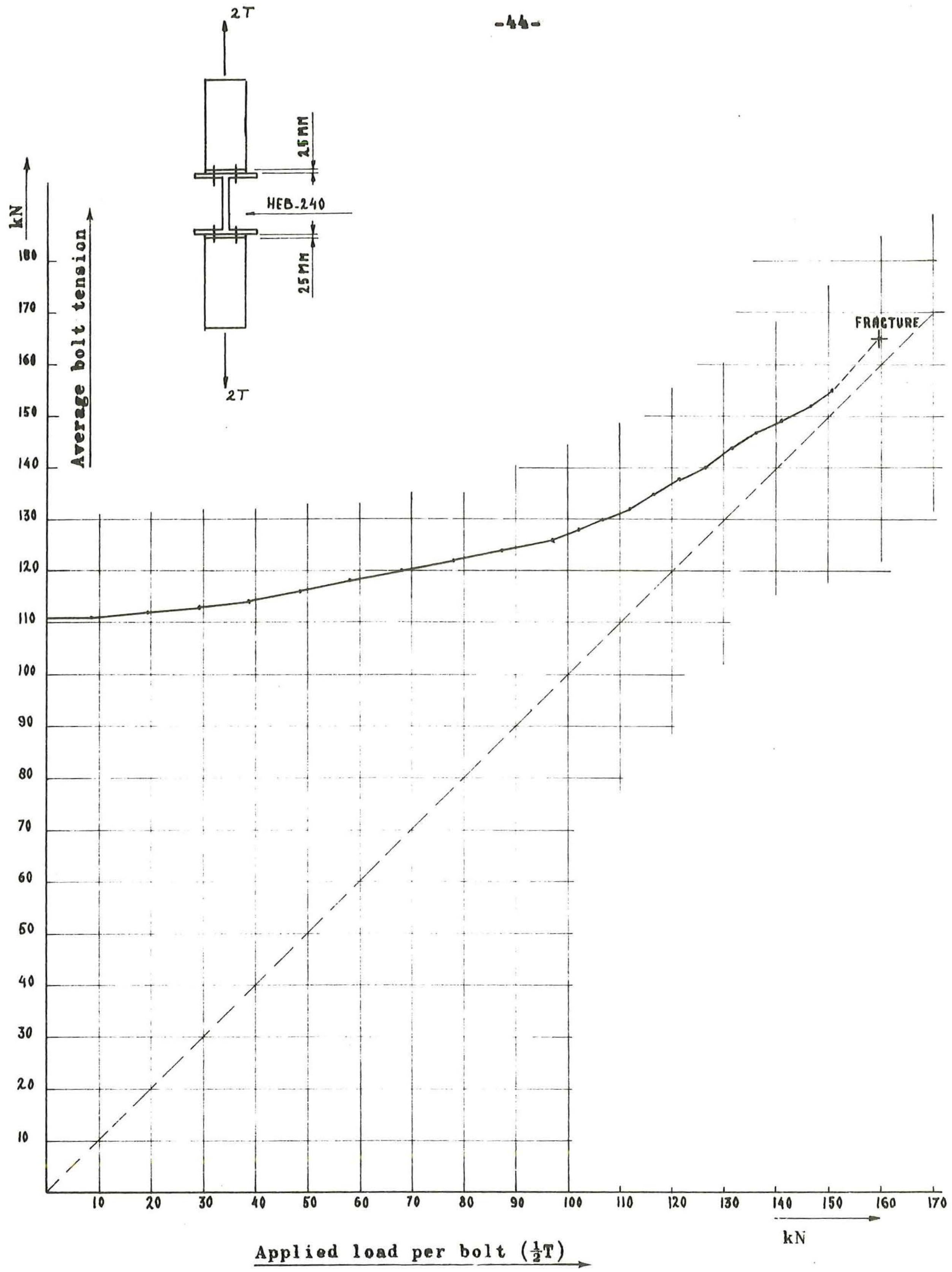
T-stub flanges 32mm

diagram 37.



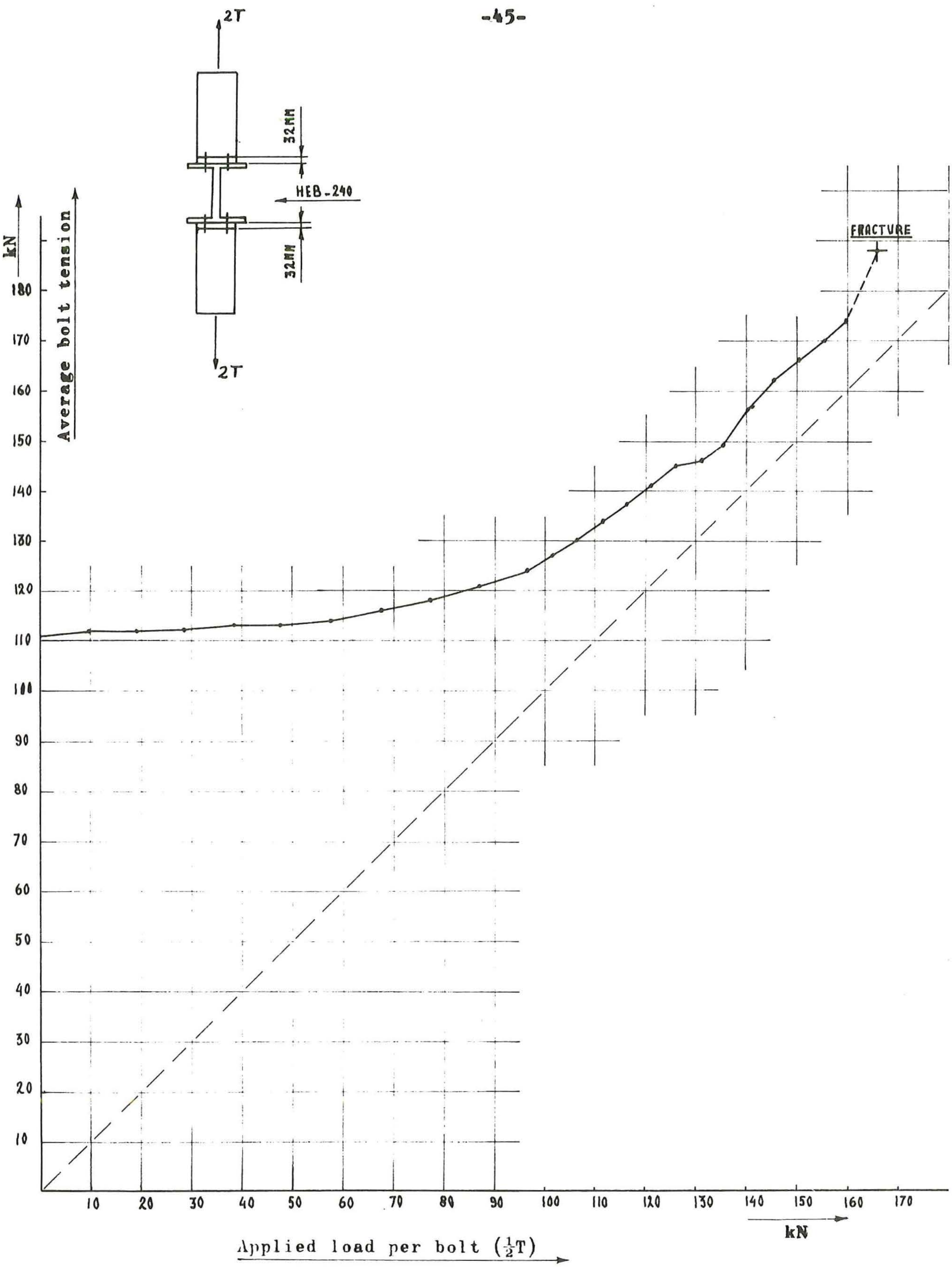
HEB-240 with T-stub flanges 20mm

diagram 39.



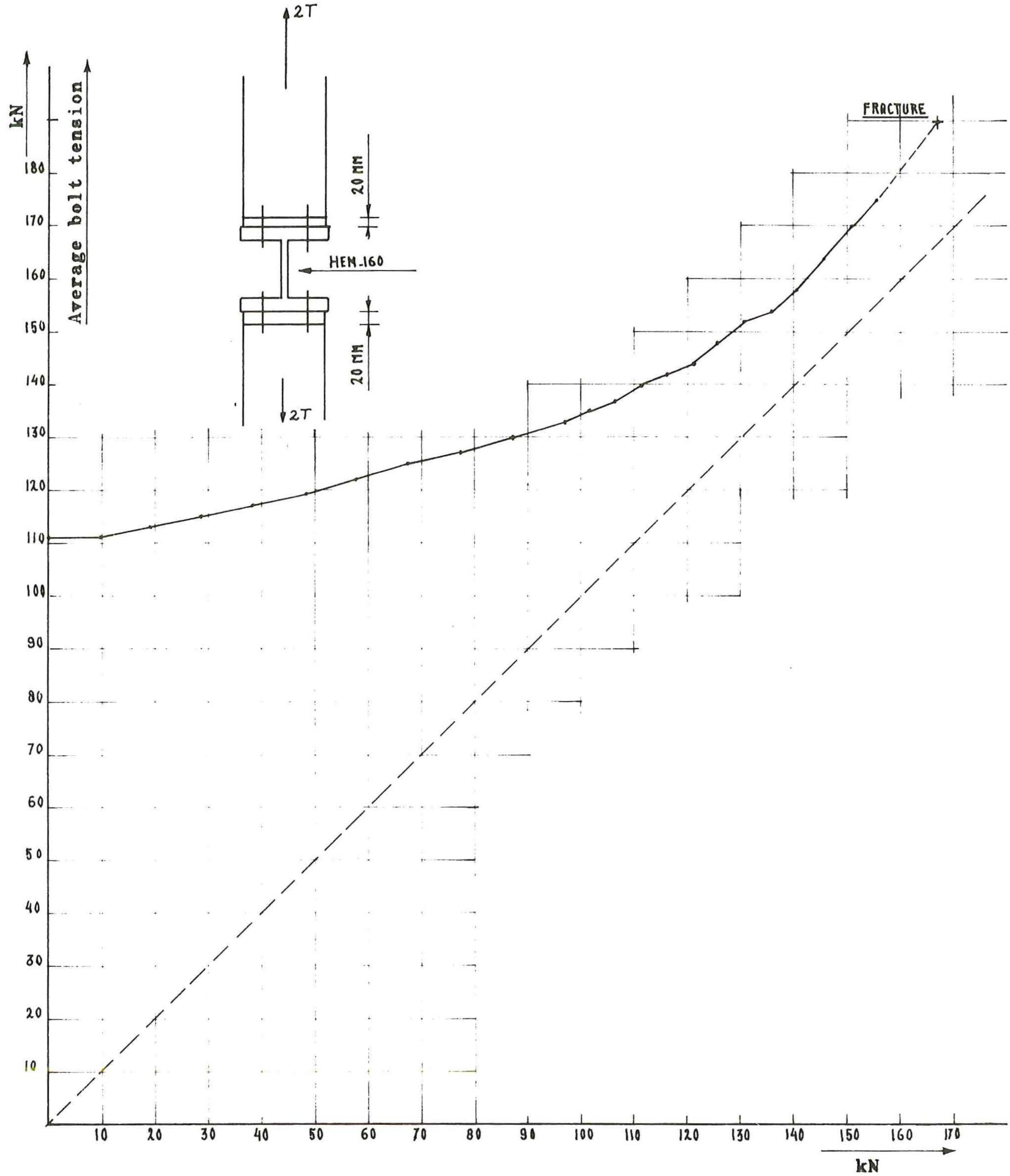
HEB-240 with T-stub flanges 25mm.

diagram 40.



HEB-240 with T-stub flanges 32mm.

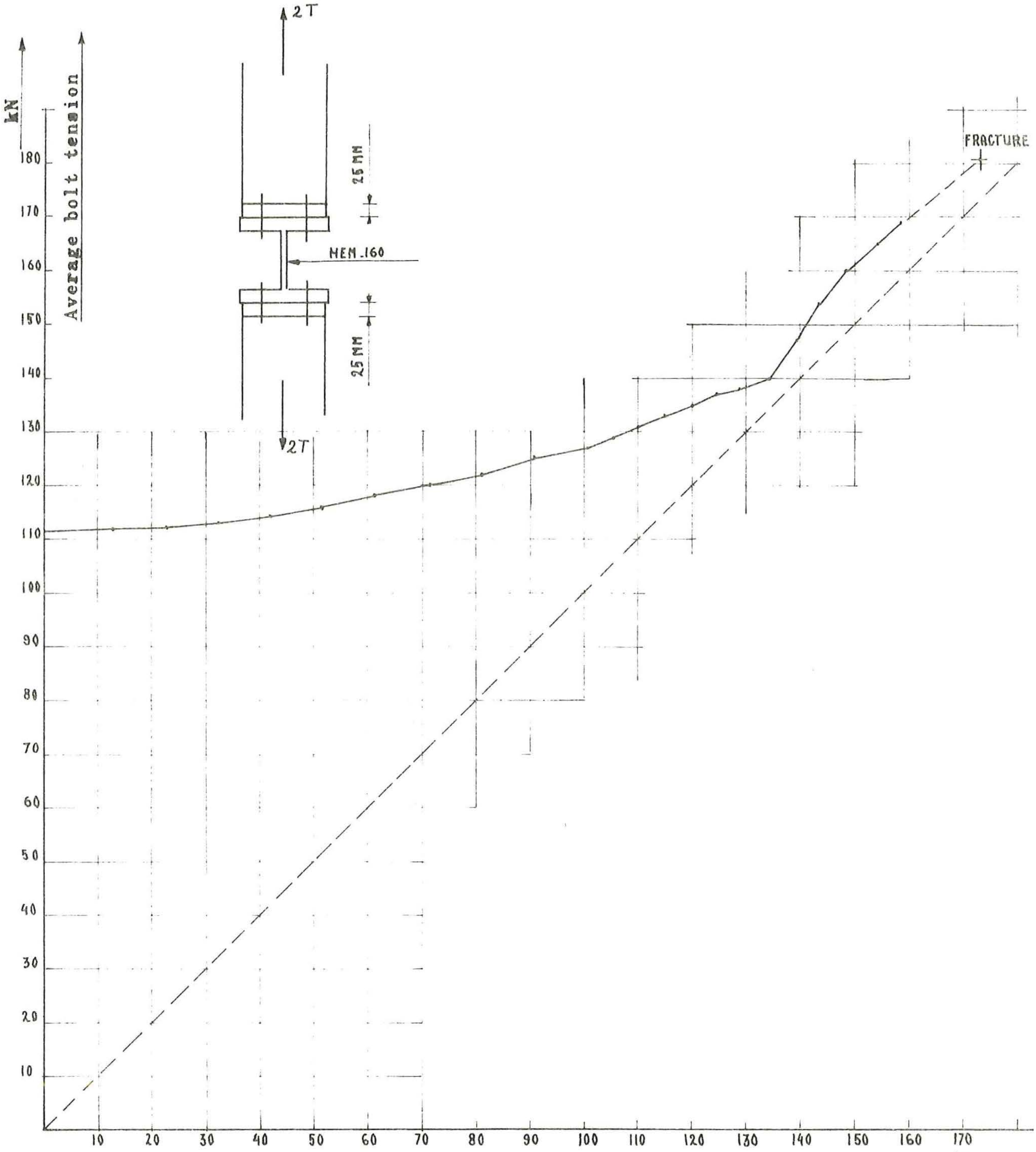
diagram 41.



Applied load per bolt ($\frac{1}{2}$T)

HEM-160 with T-stub flanges 20mm.

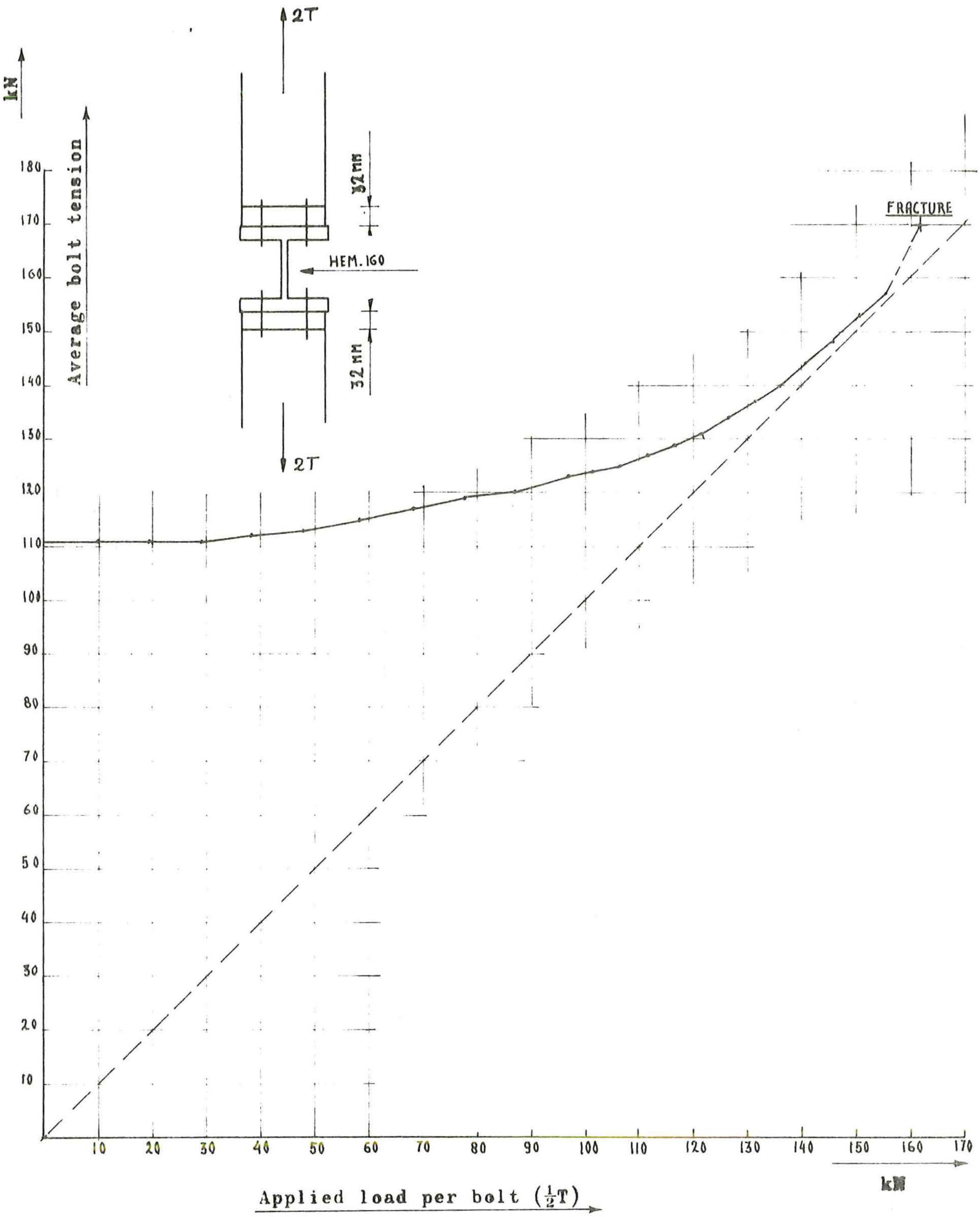
diagram 42.



Applied load per bolt ($\frac{1}{2}$T)

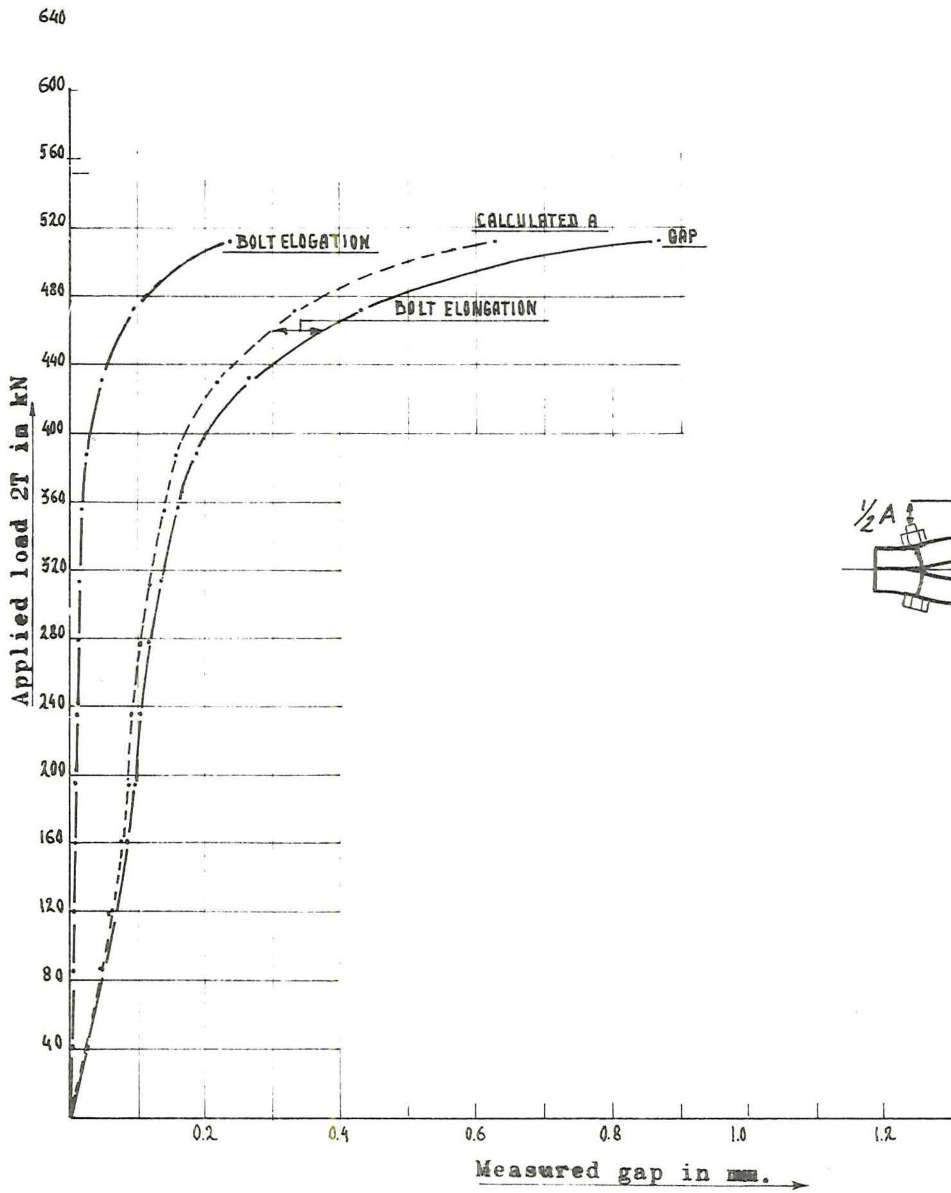
HEM-160 with T-stub flanges 25mm.

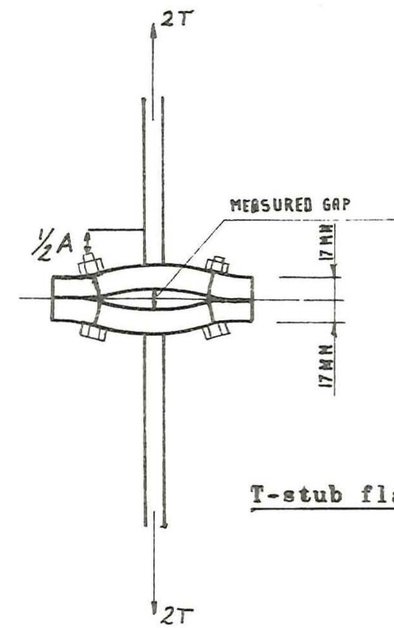
diagram 43.



HEM-160 with T-stub flanges 32mm.

diagram 44.





T-stub flanges. 17mm.

diagram 45.

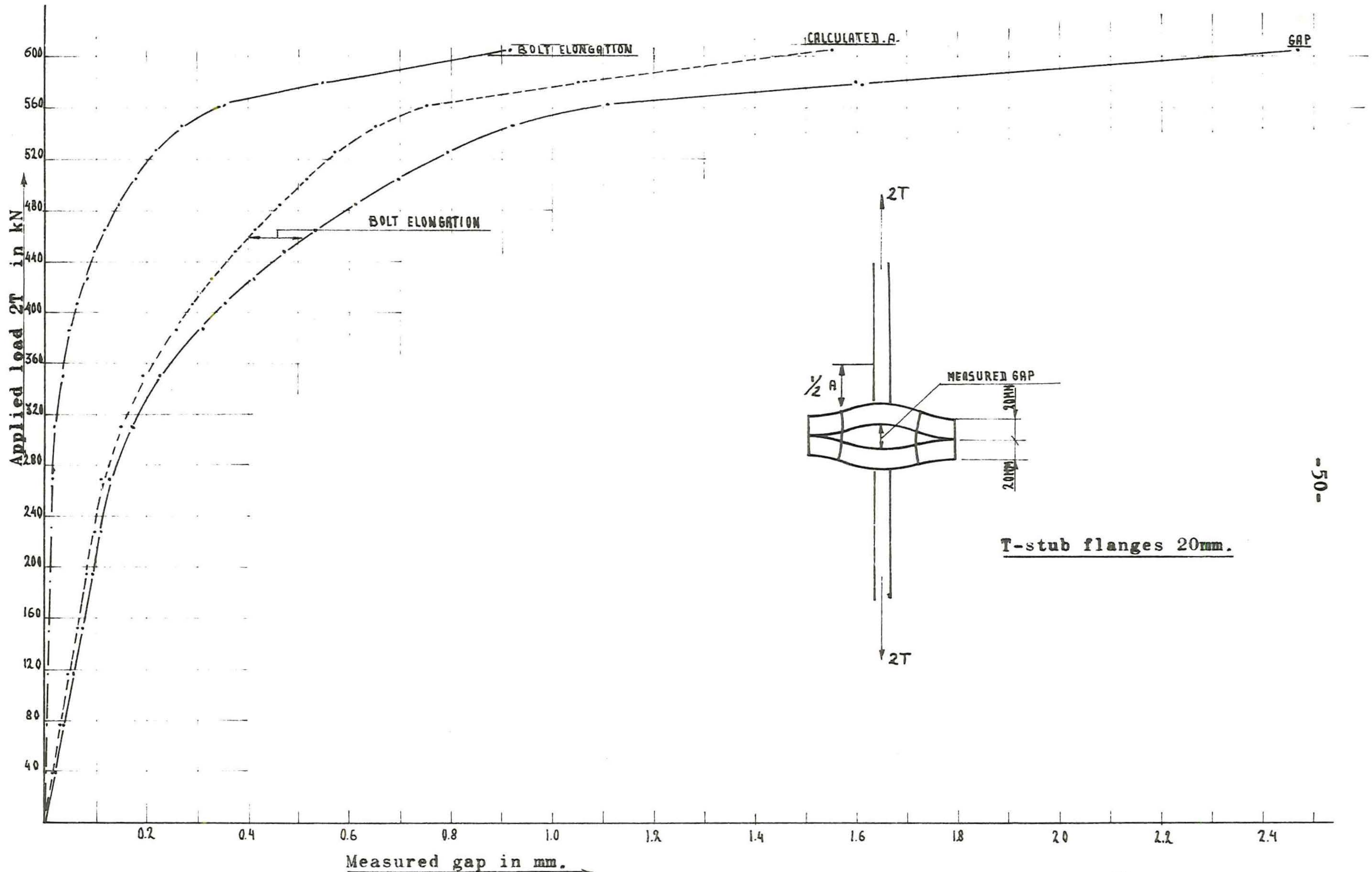
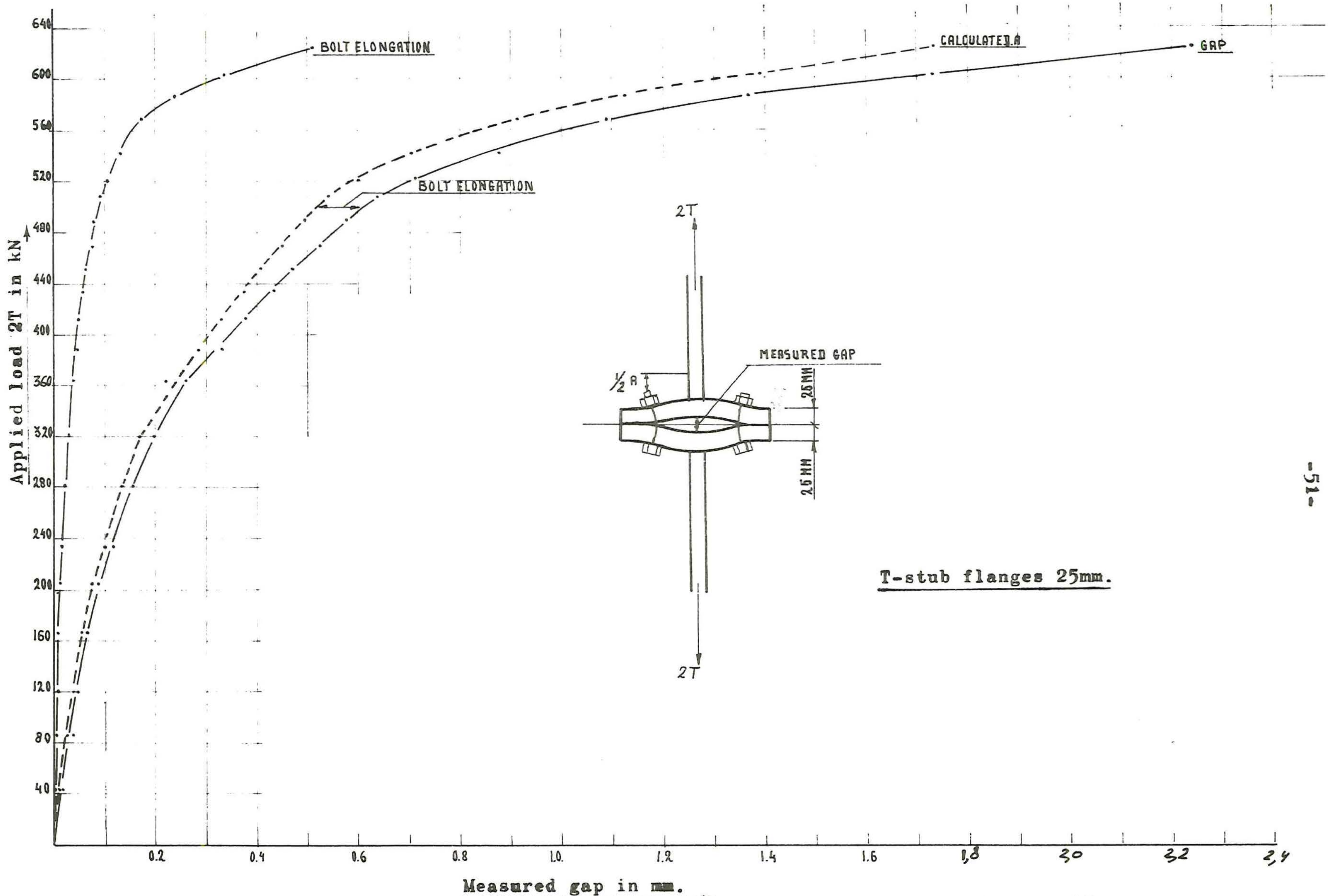
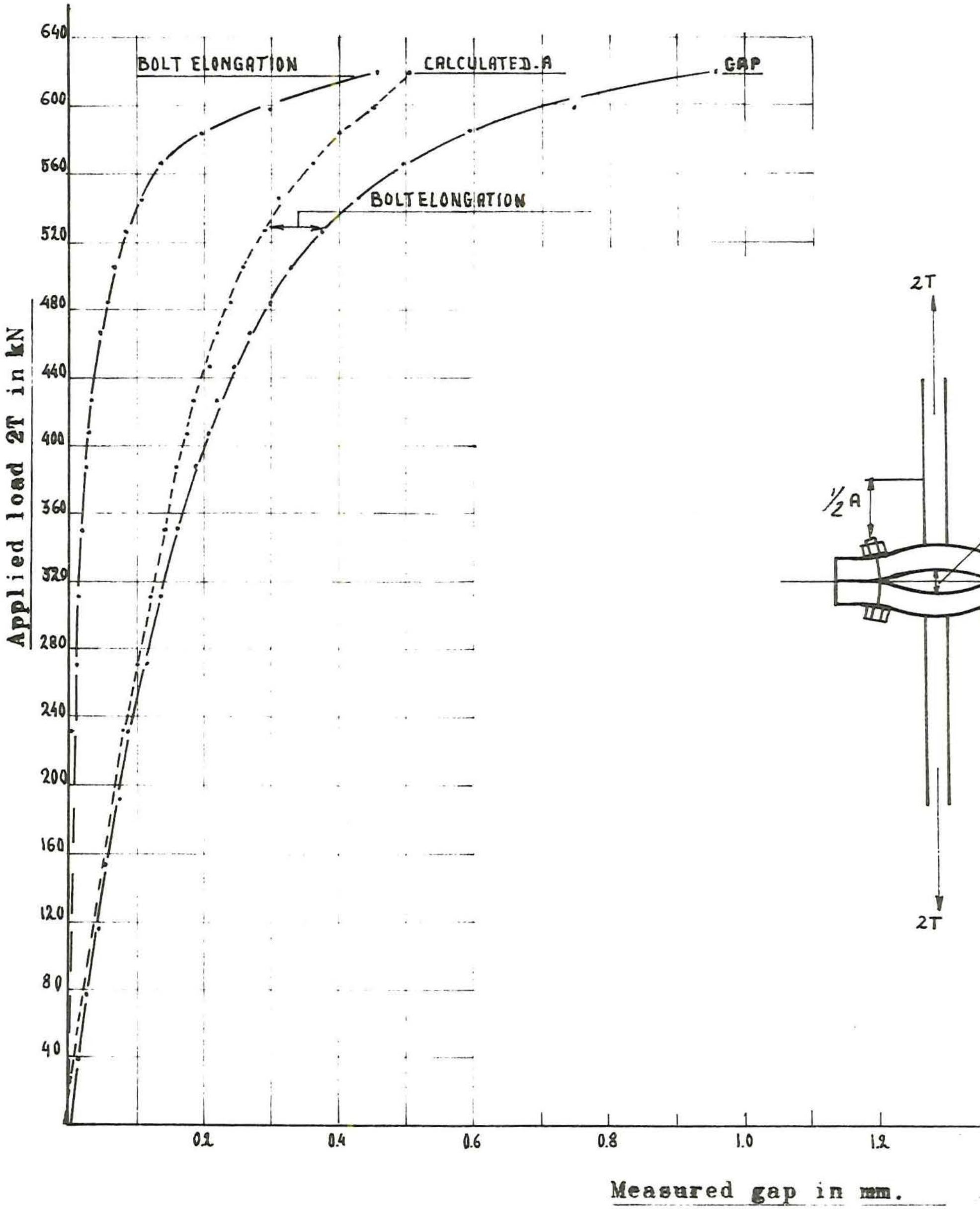

T-stub flanges 20mm.
BOLT ELONGATION
CALCULATED A
GAP
BOLT ELONGATION
2T
2T
1/2 A
MEASURED GAP
20MM
20MM
Applied load 2T in kN
600
560
520
480
440
400
360
320
280
240
200
160
120
80
40
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
Measured gap in mm.

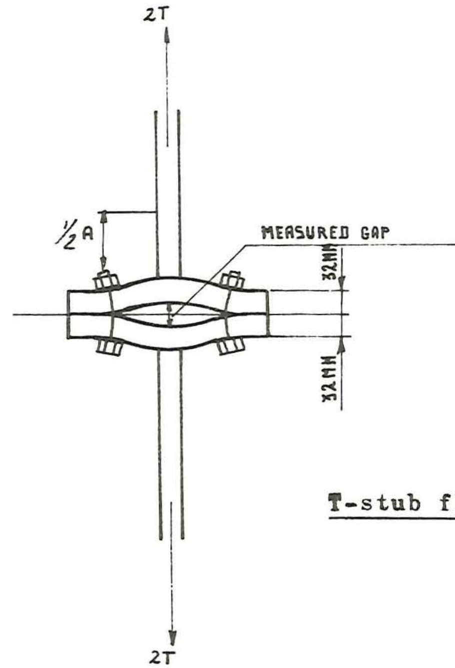
diagram 46.



T-stub flanges 25mm.

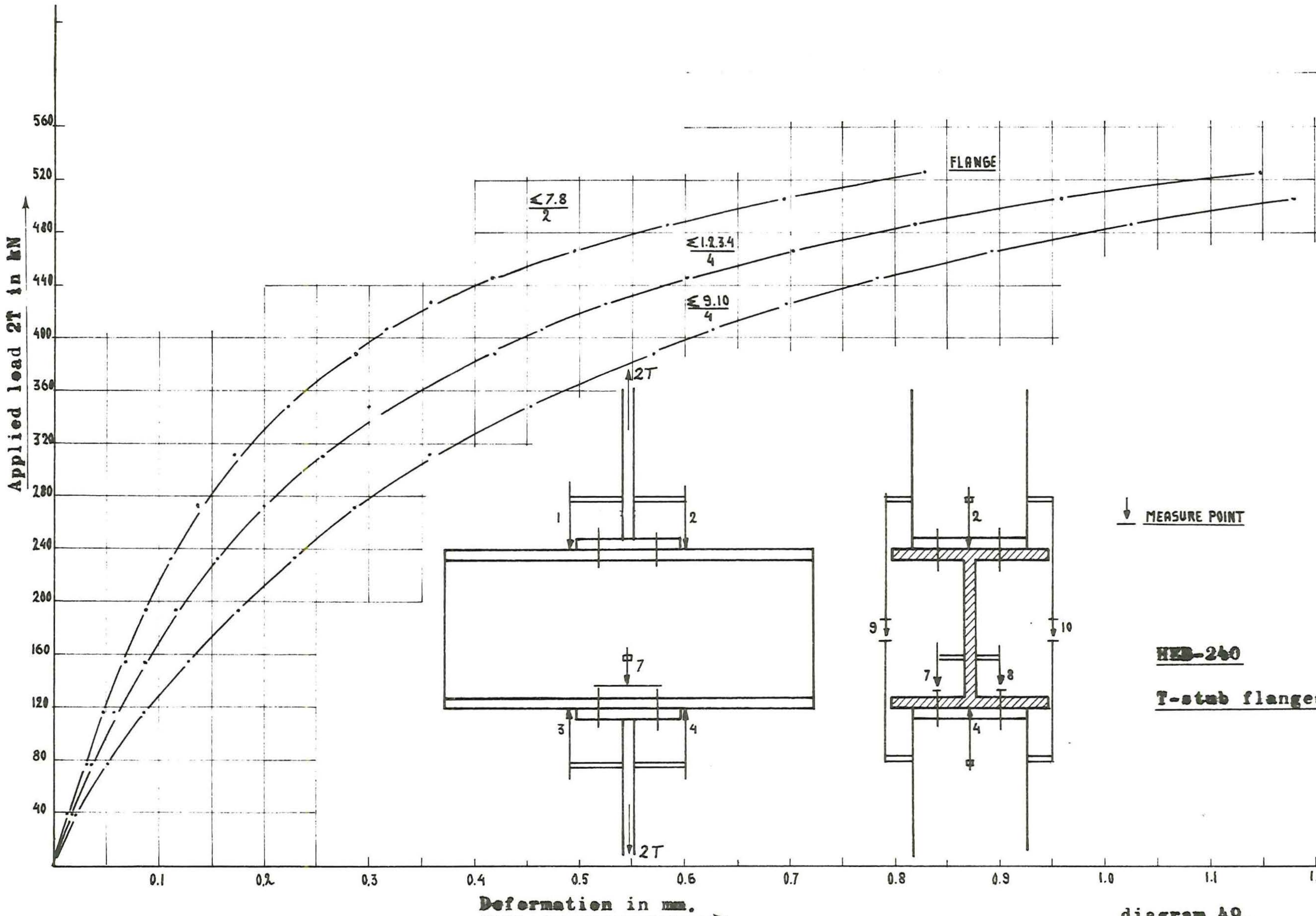
diagram 47.





T-stub flanges 32mm.

diagram 48.



HEB-240

T-stub flanges 20mm.

diagram 49.

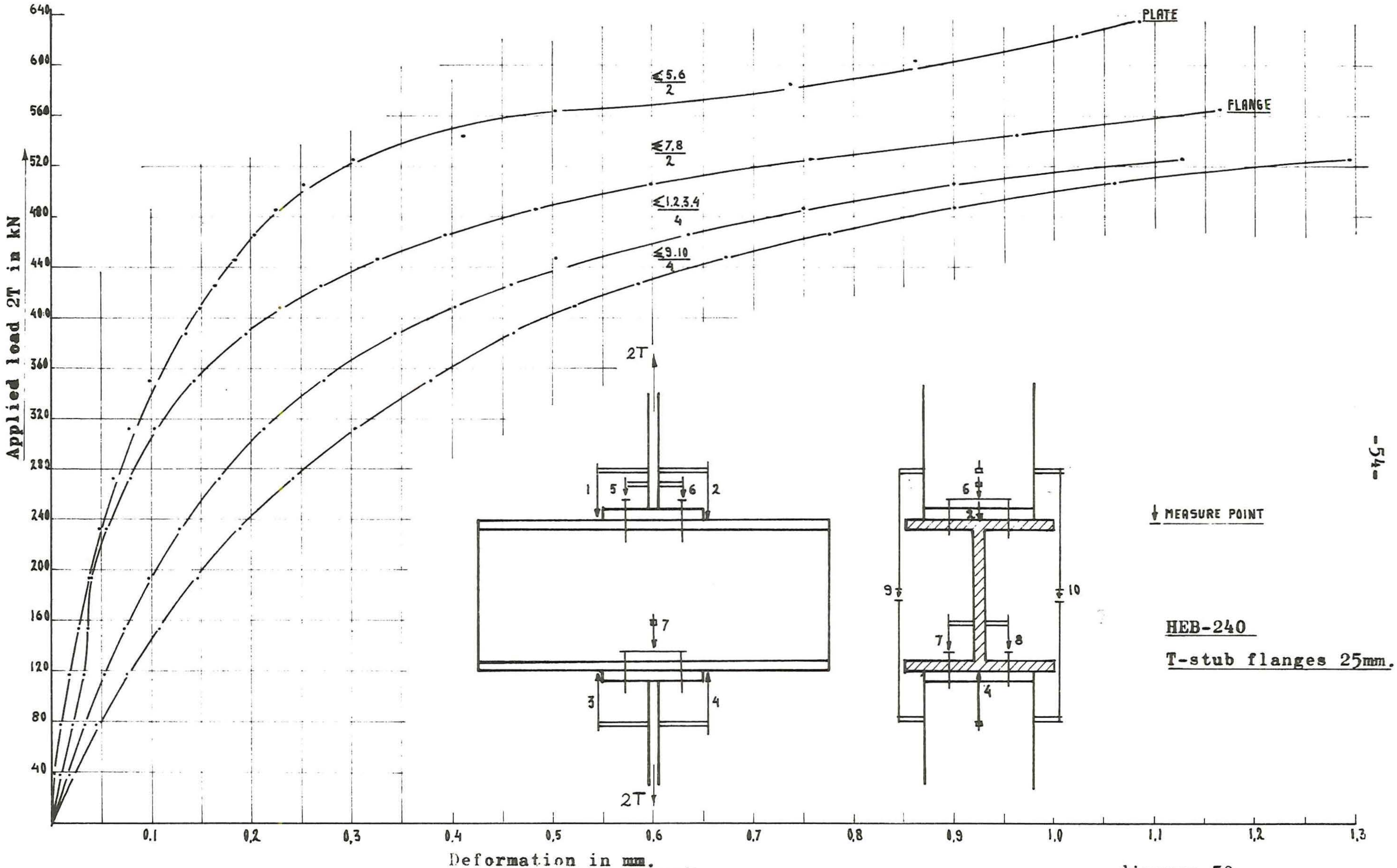


PLATE
FLANGE
≤5,6 / 2
≤7,8 / 2
≤1,2,3,4 / 4
≤9,10 / 4
Applied load 2T in kN
Deformation in mm.
2T
MEASURE POINT
HEB-240
T-stub flanges 25mm.

diagram 50.

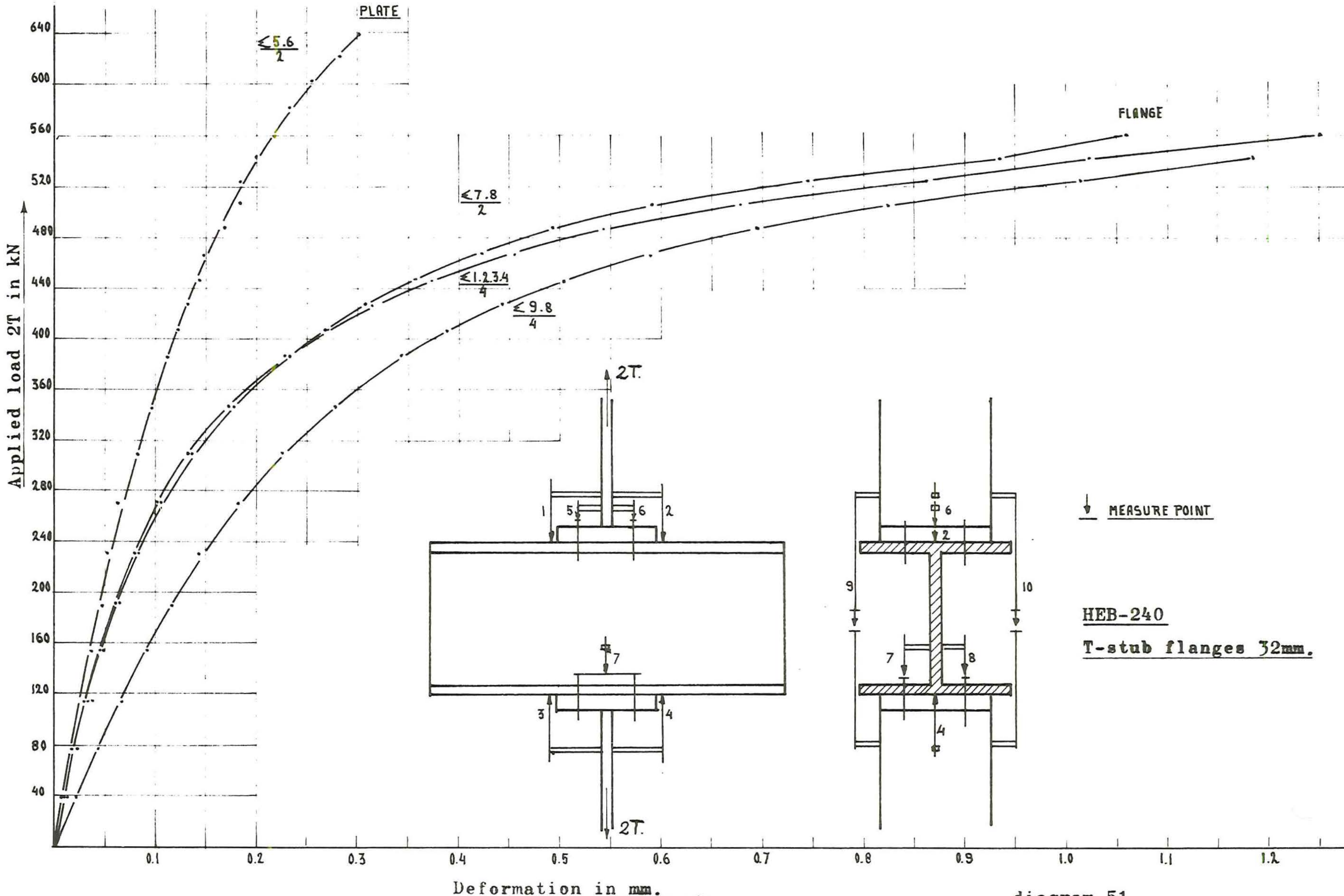
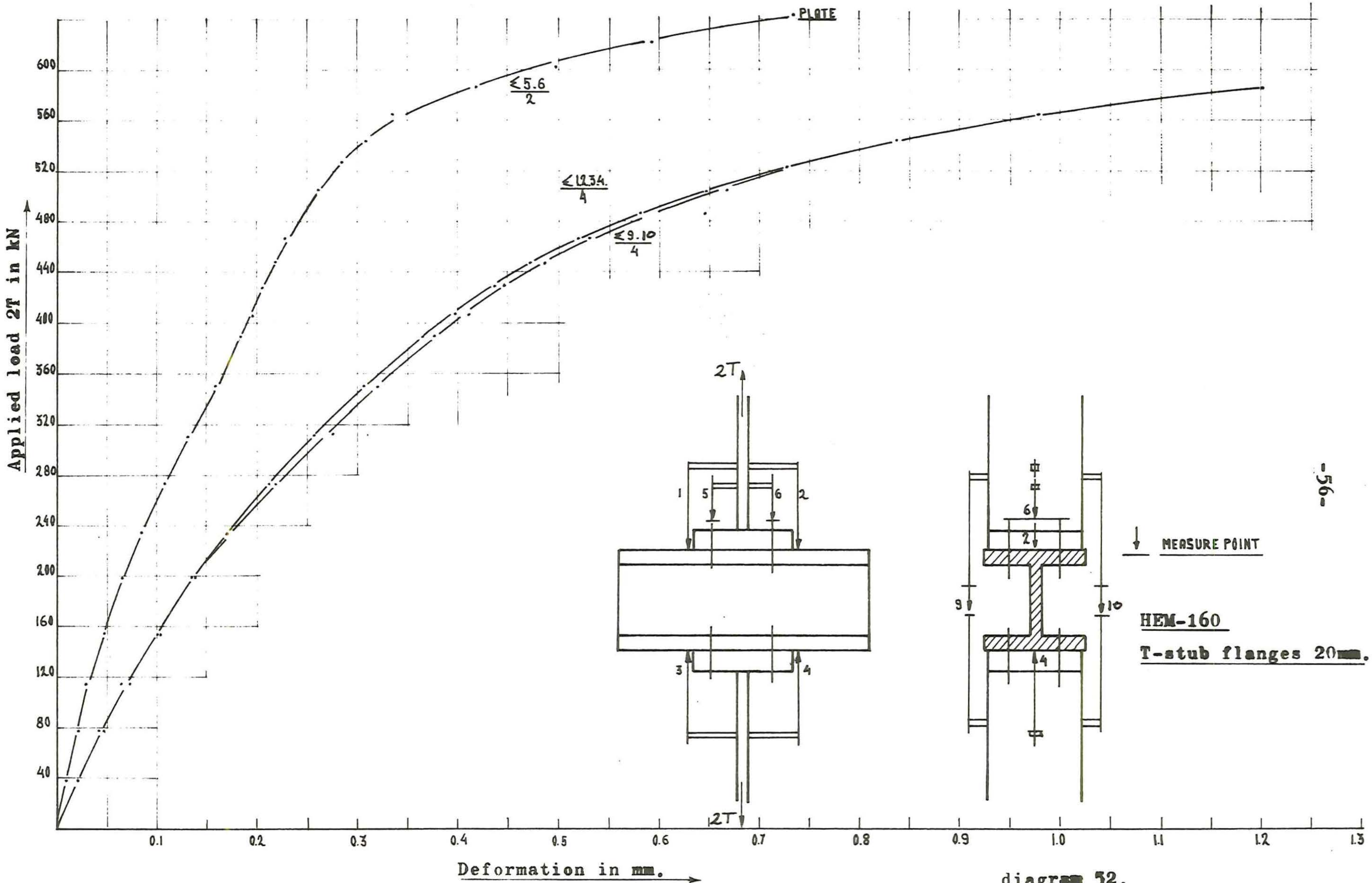


PLATE
FLANGE
≤ 5.6 / 2
≤ 7.8 / 2
≤ 1.2.3.4 / 4
≤ 9.8 / 4
Applied load 2T in kN
Deformation in mm.
2T
MEASURE POINT
HEB-240
T-stub flanges 32mm.

diagram 51.



Applied load 2T in kN
600
560
520
480
440
400
360
320
280
240
200
160
120
80
40
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
Deformation in mm.
PLATE
≤5.6/2
≤1.2.3.4./4
≤9.10/4
2T
2T
1
5
6
2
3
4
6
2
9
10
4
MEASURE POINT
HEM-160
T-stub flanges 20mm.

diagram 52.

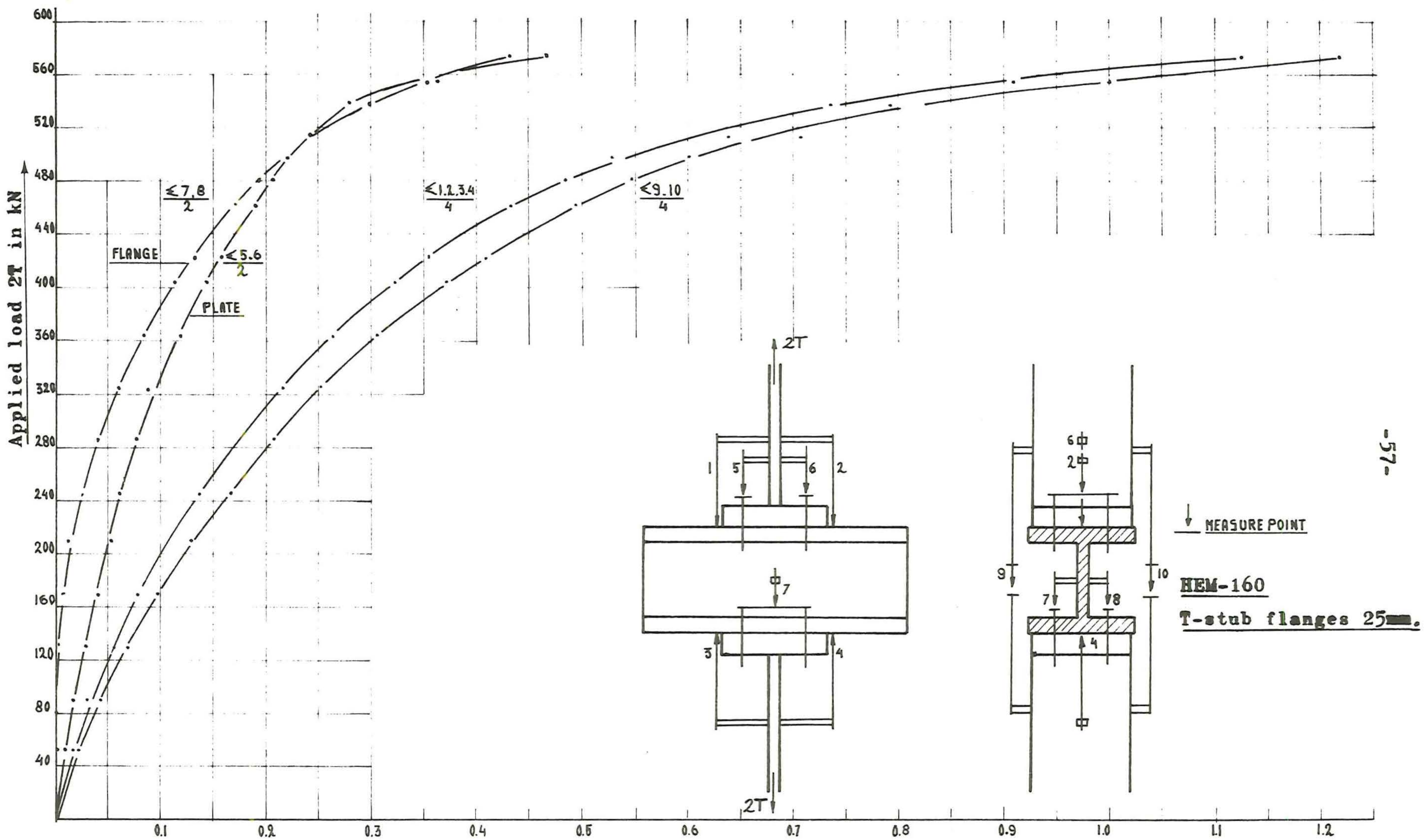

Applied load 2T in kN
600
560
520
480
440
400
360
320
280
240
200
160
120
80
40
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
Deformation in mm.
≤7,8 / 2
FLANGE
≤5.6 / 2
PLATE
≤1.2.3.4 / 4
≤9.10 / 4
2T
1
2
3
4
5
6
7
8
9
10
MEASURE POINT
HEM-160
T-stub flanges 25mm.

diagram 53.

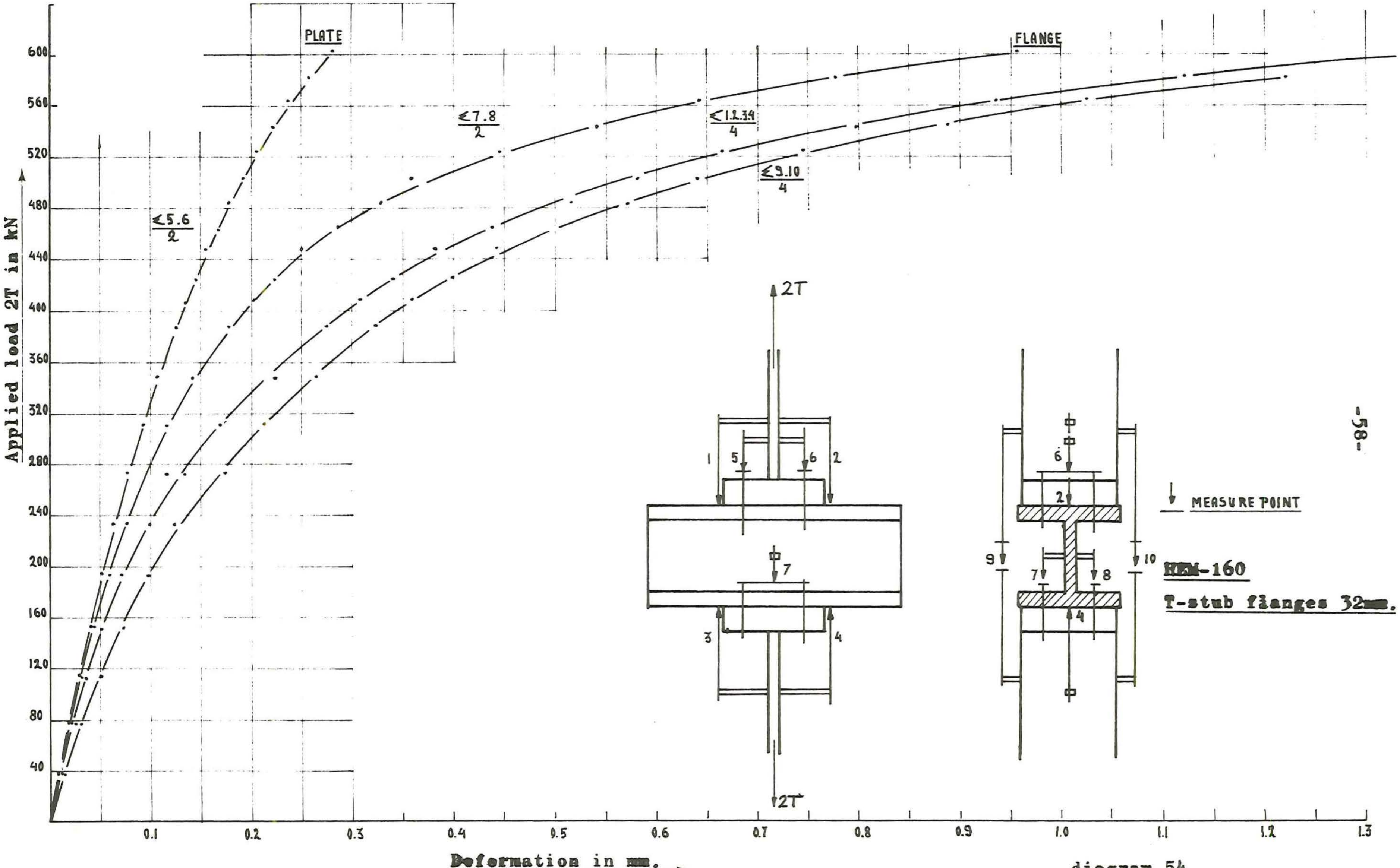
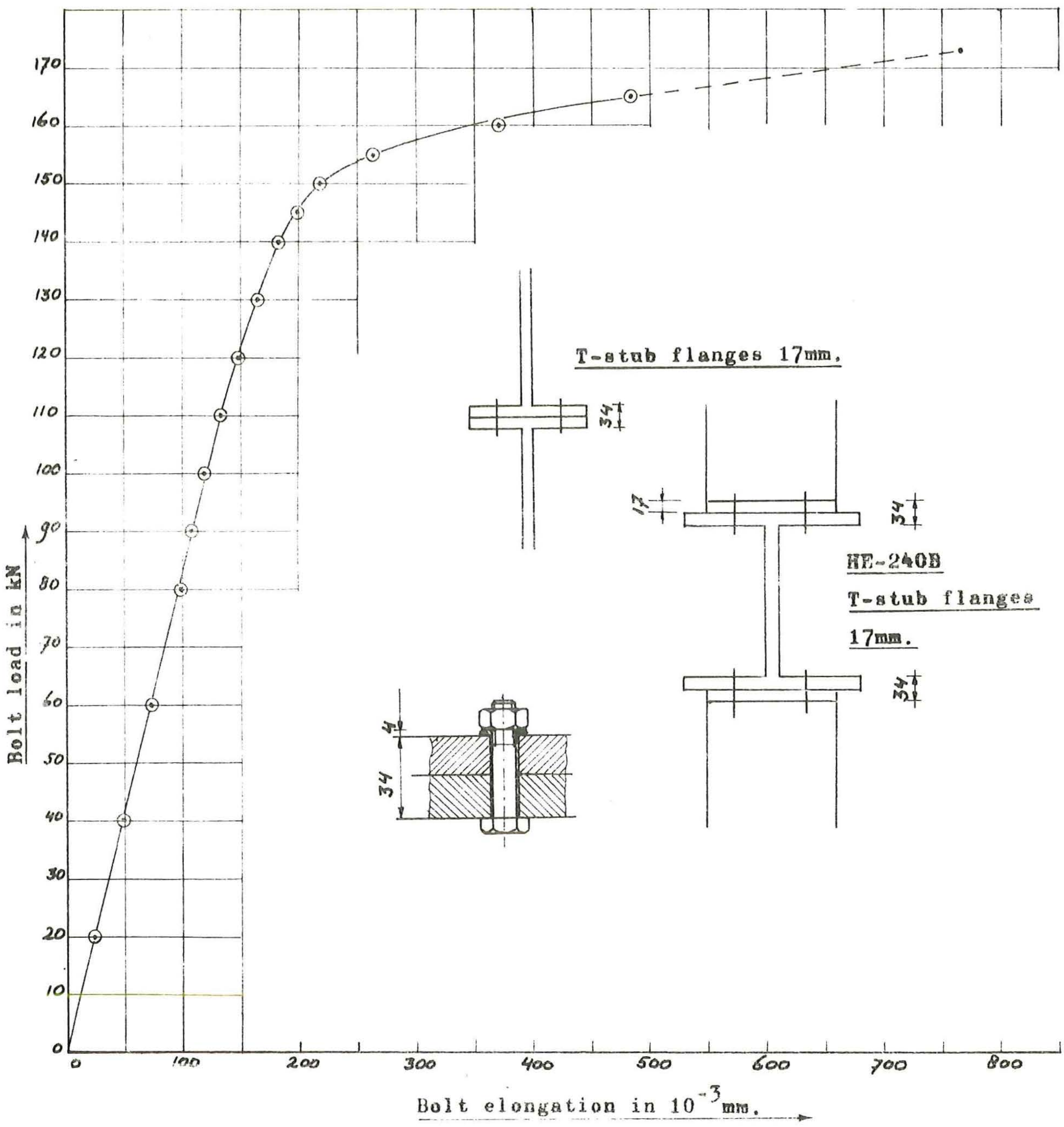
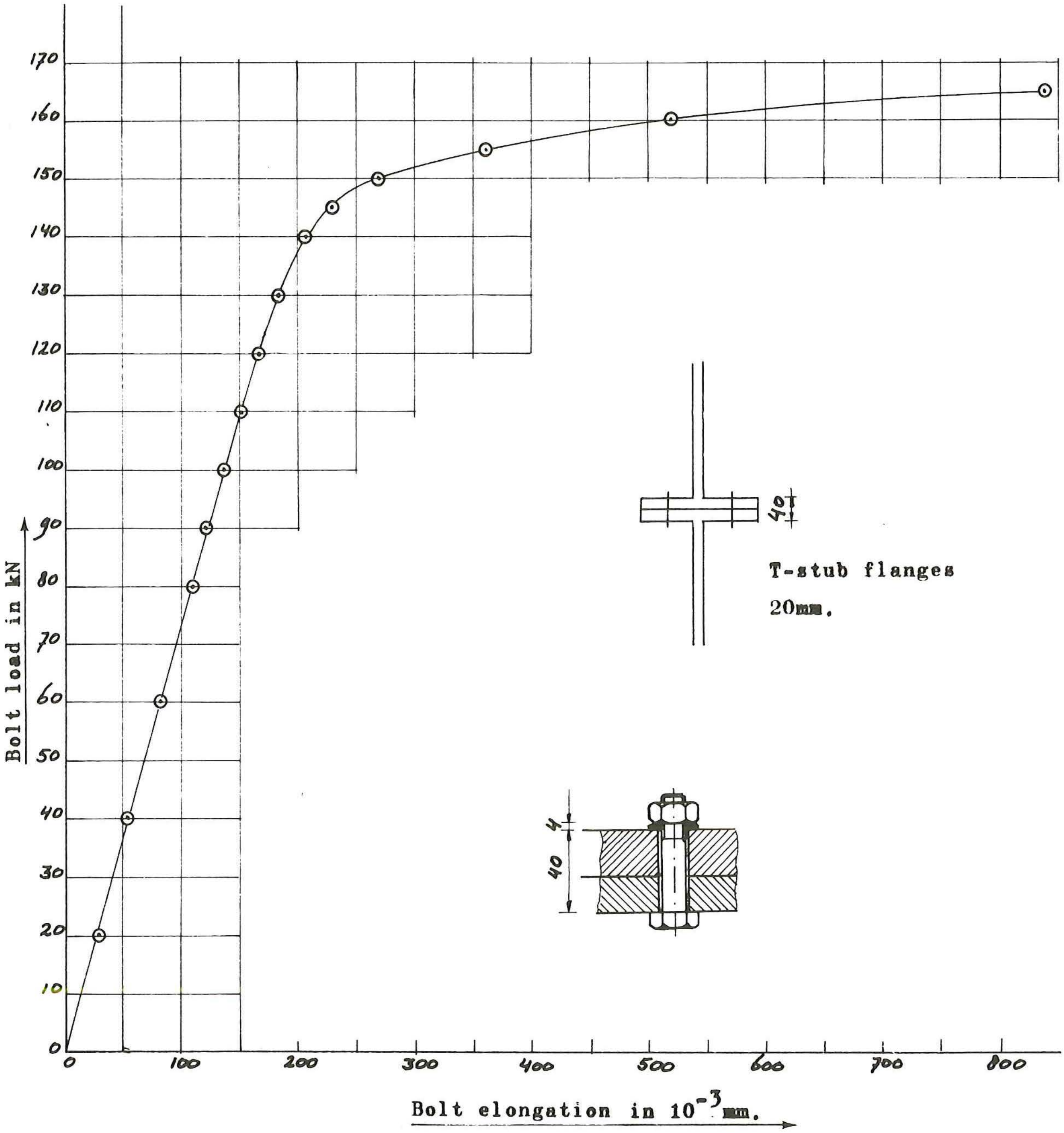


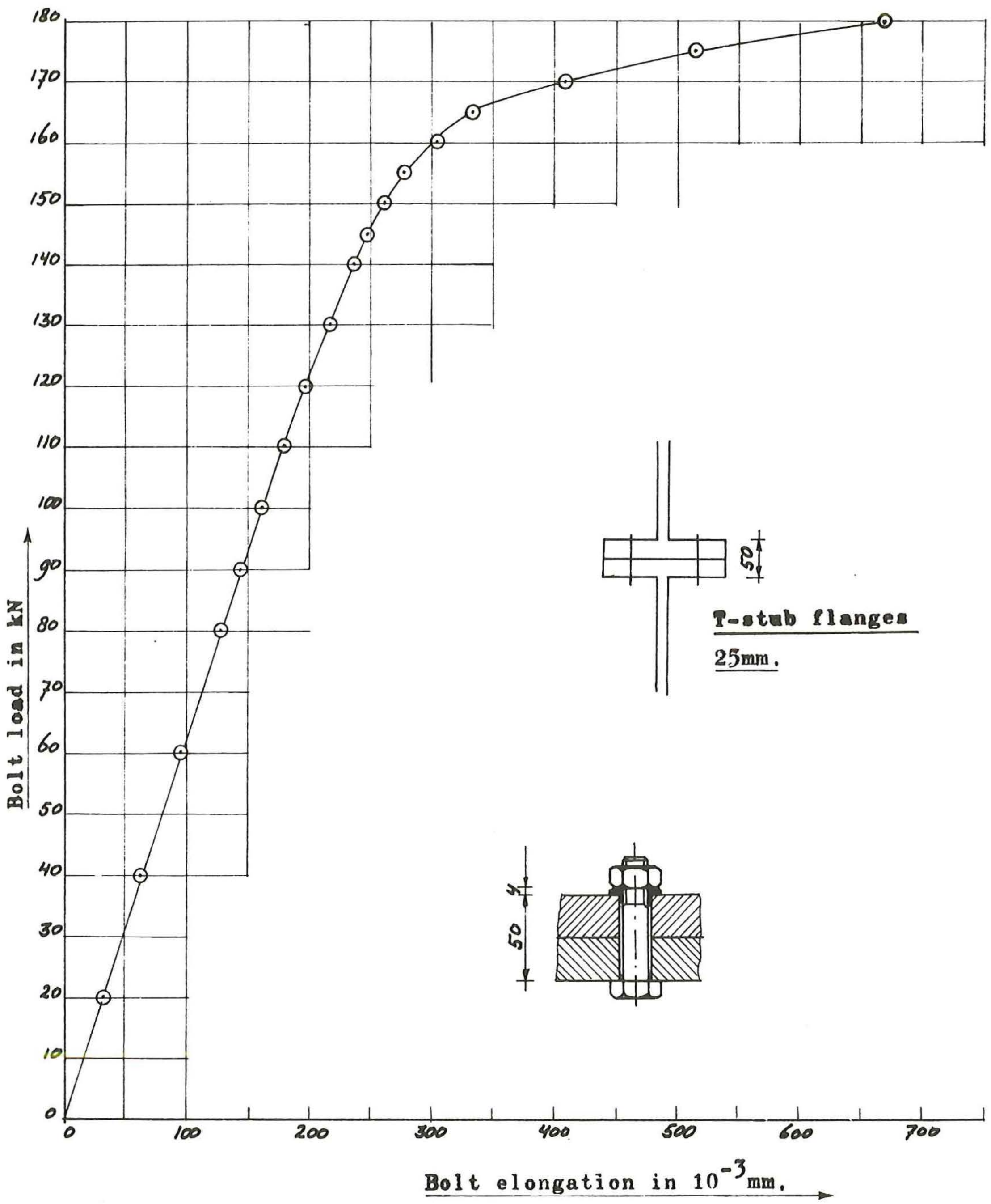
PLATE
FLANGE
≤5.6 / 2
≤7.8 / 2
≤12.34 / 4
≤9.10 / 4
Applied load 2T in kN
Deformation in mm.
2T
MEASURE POINT
HEM-160
T-stub flanges 32mm.

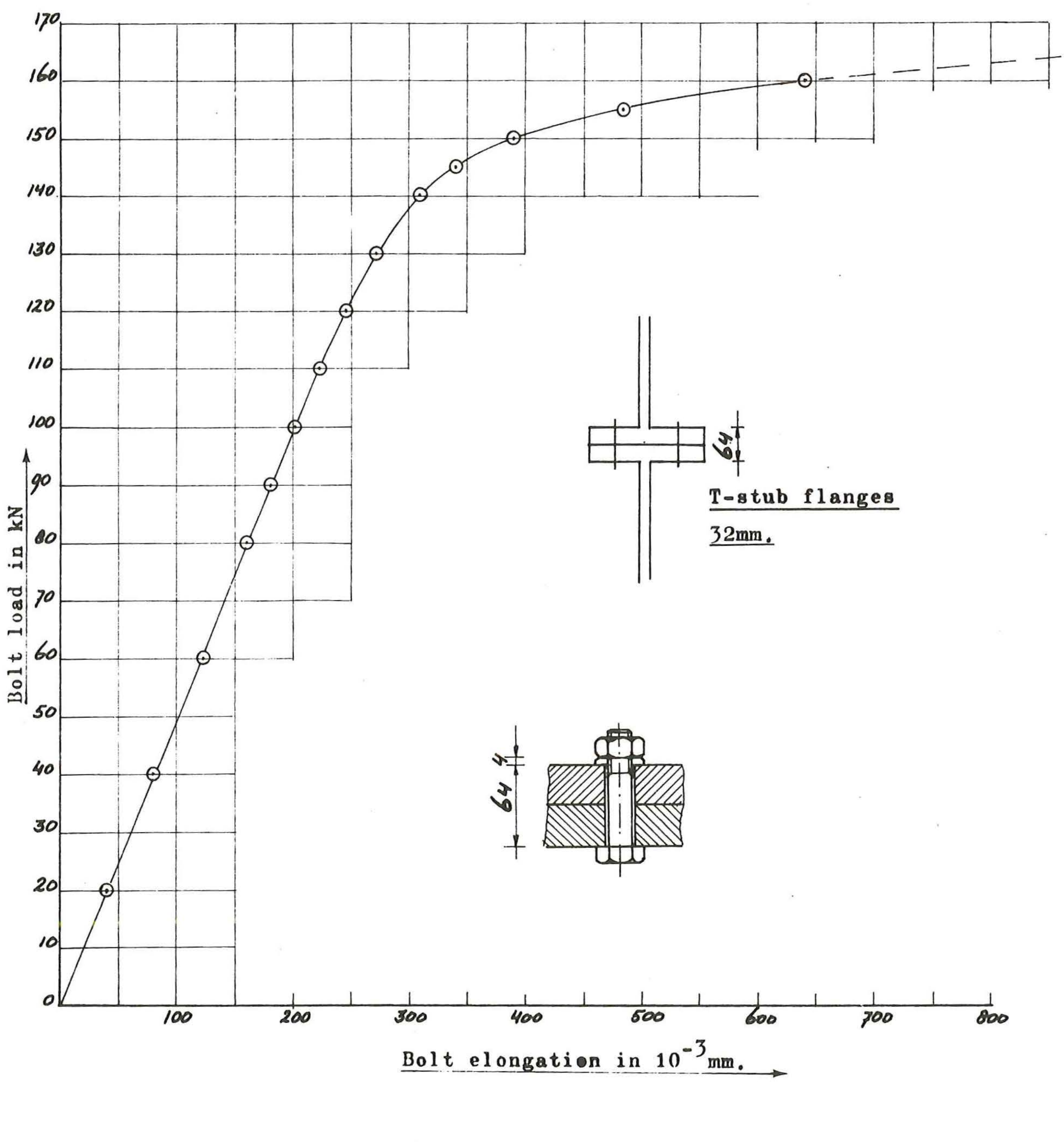
diagram 54.


170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Bolt load in kN
0
100
200
300
400
500
600
700
800
Bolt elongation in 10^{-3}mm.
T-stub flanges 17mm.
34
17
34
HE-240B
T-stub flanges
17mm.
34
4
34

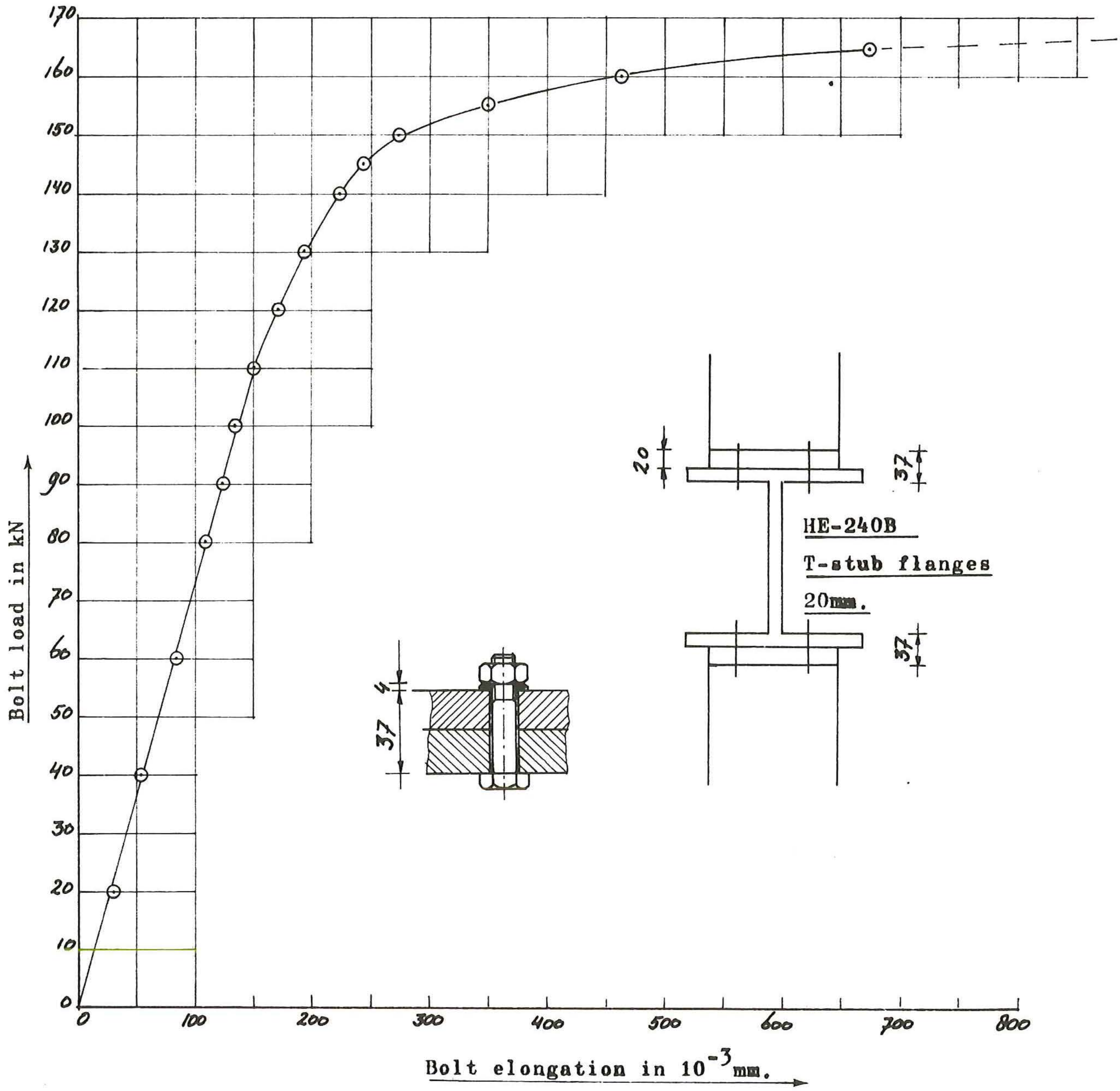


Bolt load in kN
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
0
100
200
300
400
500
600
700
800
Bolt elongation in 10^{-3} mm.
T-stub flanges
20mm.
40
4
40

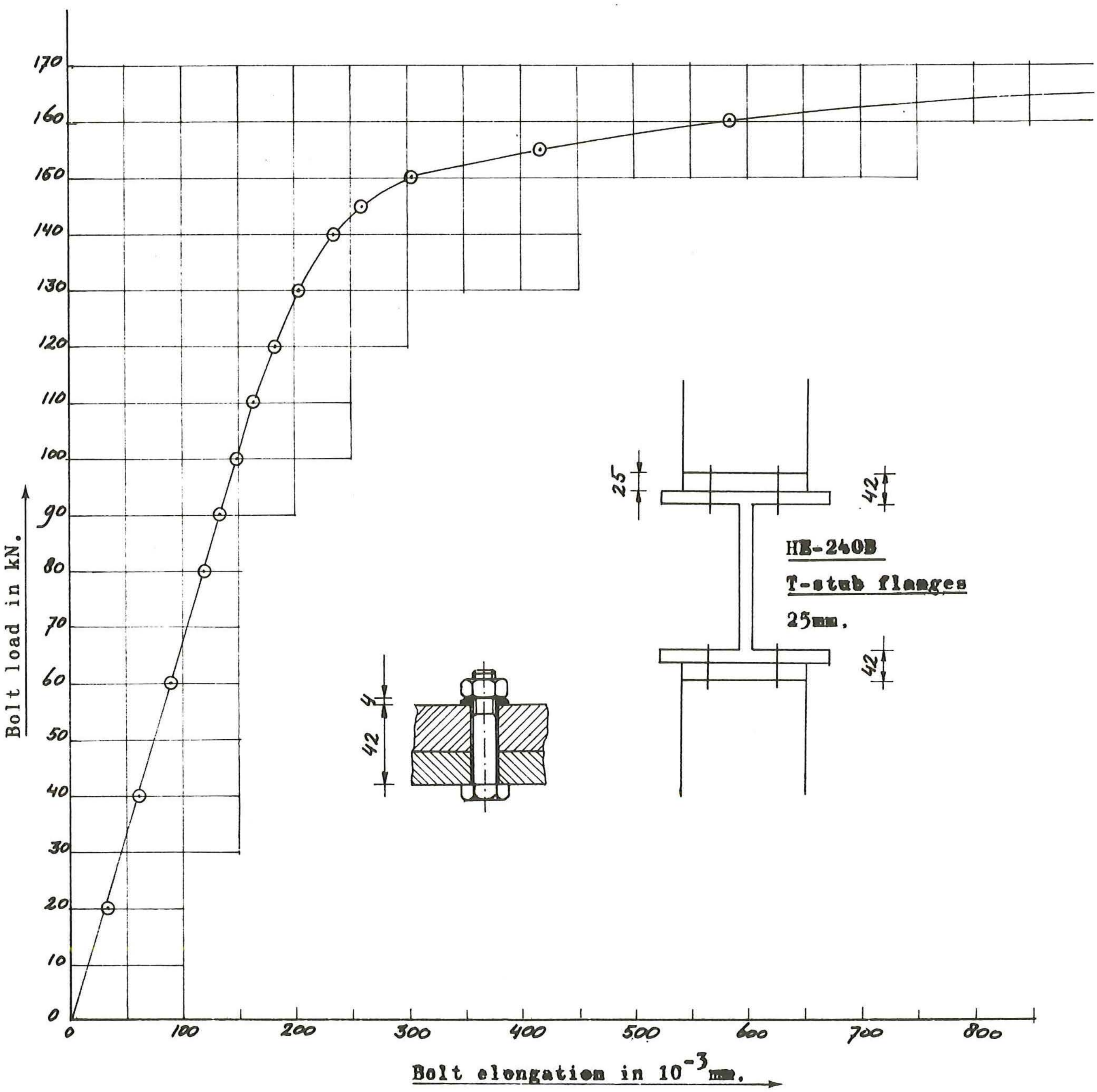

Bolt load in kN
Bolt elongation in 10^{-3}mm.
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
0
100
200
300
400
500
600
700
50
T-stub flanges
25mm.
4
50

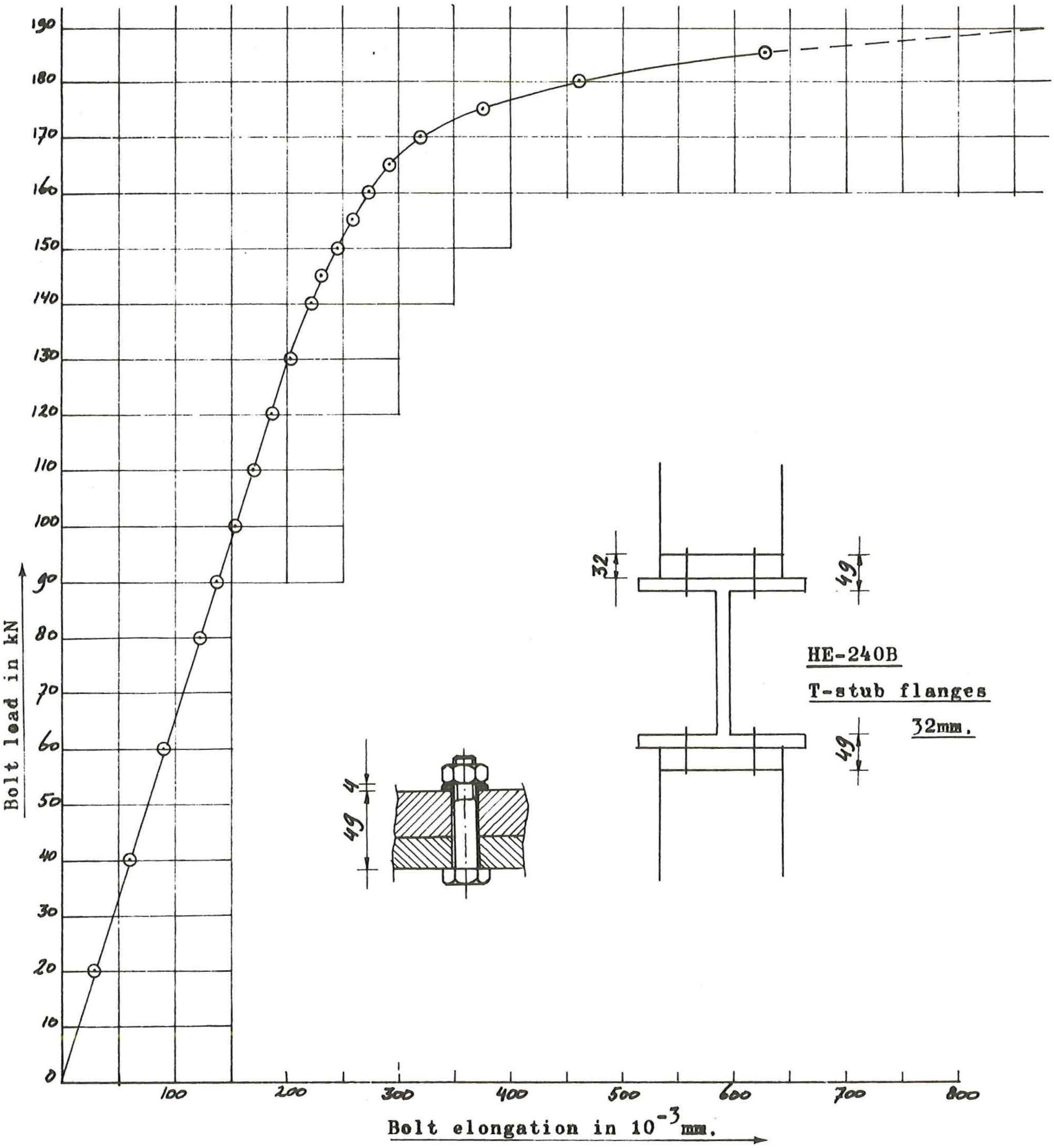


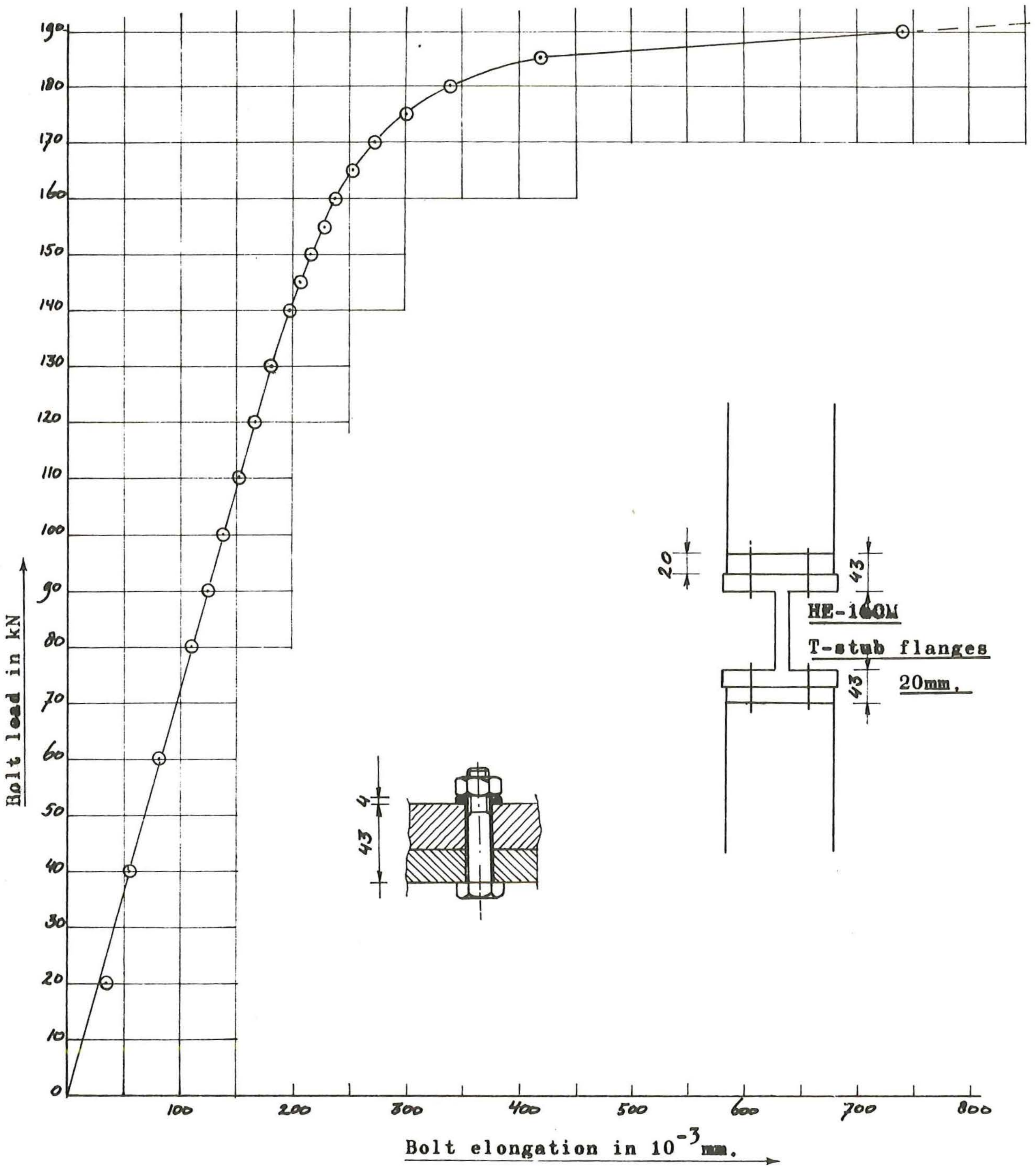
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
100
200
300
400
500
600
700
800
Bolt load in kN
Bolt elongation in 10^{-3}mm.
64
T-stub flanges
32mm.
4
64



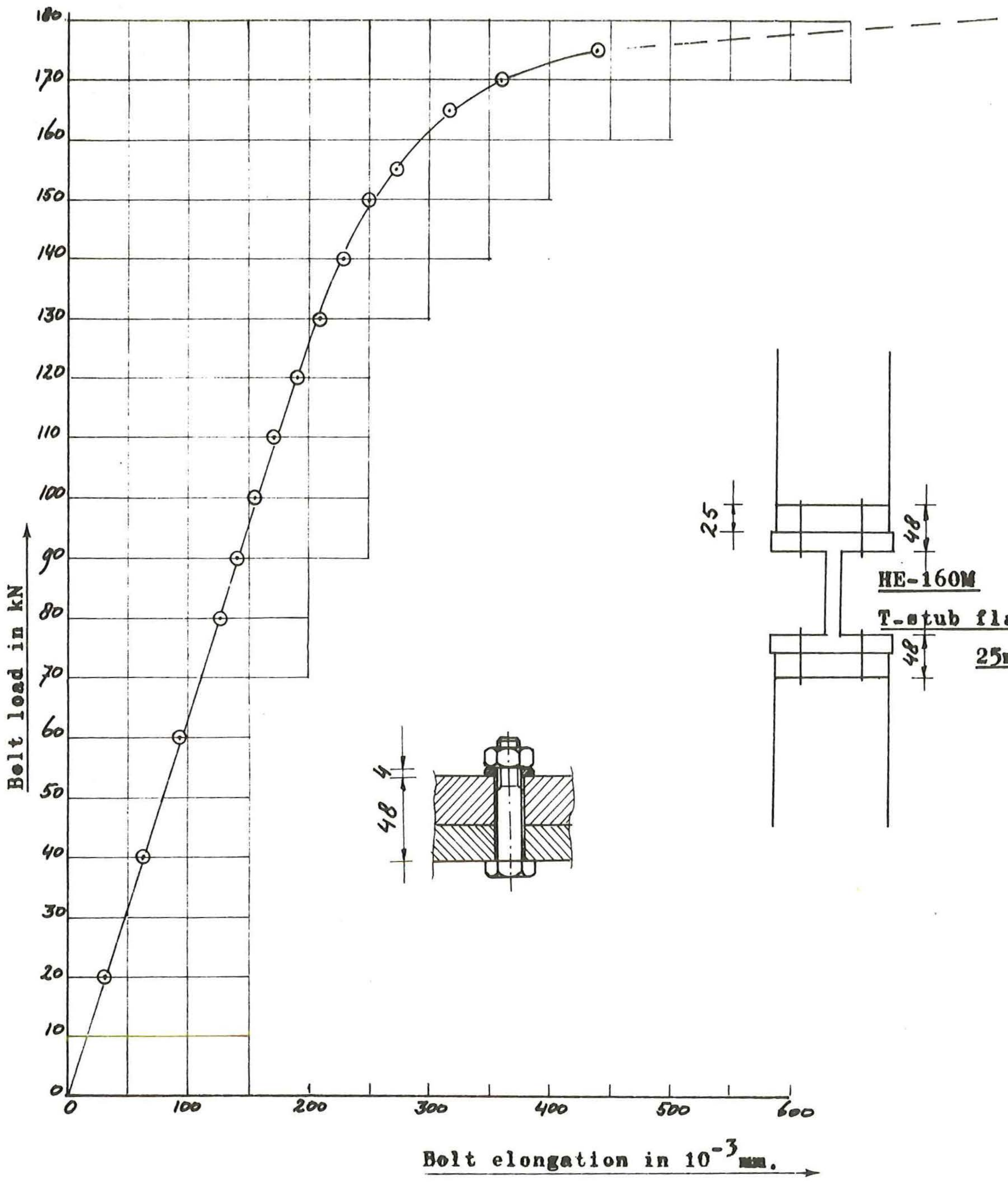
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
800
Bolt load in kN
Bolt elongation in 10^{-3}mm.
HE-240B
T-stub flanges
20mm.
20
37
37
4
37


Bolt load in kN.
170
160
160
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
800
Bolt elongation in 10^{-3} mm.
HE-240B
T-stub flanges
25mm.
25
42
42
4
42

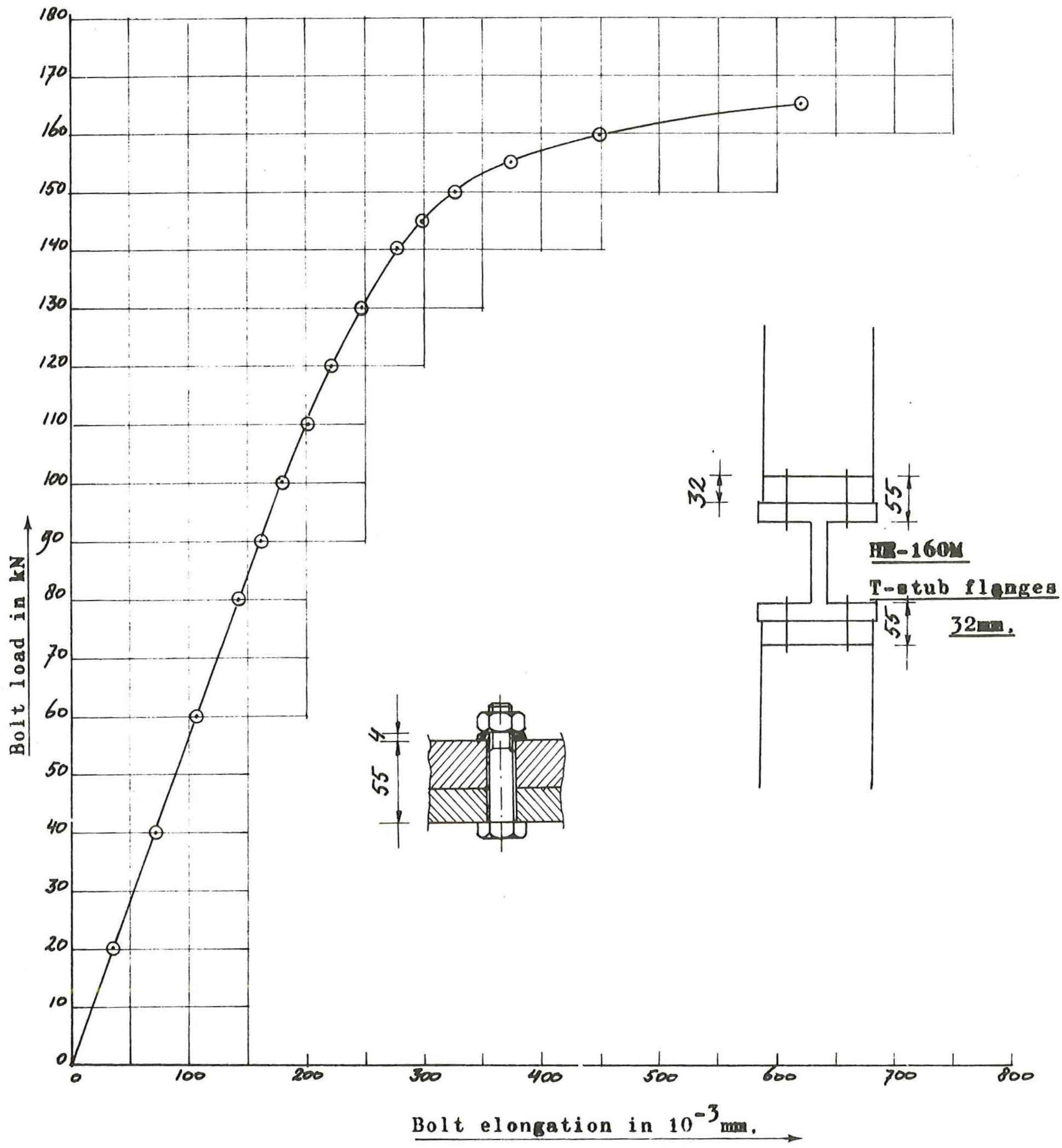

Bolt load in kN
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
100
200
300
400
500
600
700
800
Bolt elongation in 10^{-3} mm.
32
49
49
4
49
HE-240B
T-stub flanges
32mm.



Bolt load in kN
Bolt elongation in 10^{-3}mm.
HE-160M
T-stub flanges
20mm.
20
43
43
4
43
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
100
200
300
400
500
600
700
800



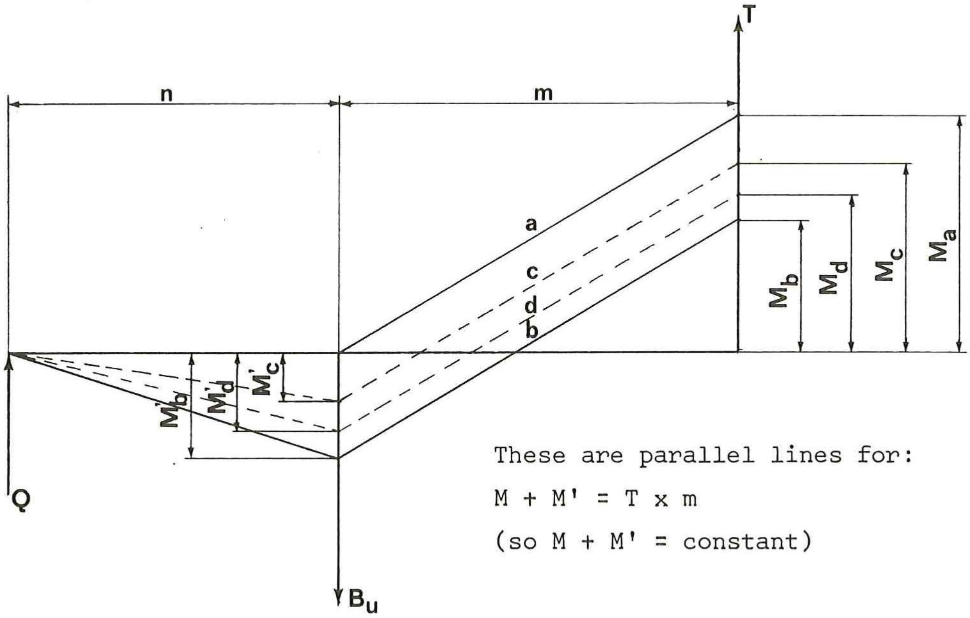
Belt load in kN
Bolt elongation in 10^{-3}mm.
HE-160M
T-stub flanges
25mm.
25
48
48
4
48
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
0
100
200
300
400
500
600



Bolt load in kN
Bolt elongation in 10^{-3}mm.
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
100
200
300
400
500
600
700
800
4
55
32
55
55
HE-160M
T-stub flanges
32mm.

Appendix A:

As stated in the report, the following situations are possible, given constant T, m and n.



These are parallel lines for:

$M + M' = T \times m$

(so $M + M'$ = constant)

case a; gives the smallest possible bolt force ($Q = 0$, so $B_u = T$) and the thickest plate.

case b; gives the thinnest possible plate ($M = M_v$, $M' = M_v'$) and the largest bolt force ($M_v' = Q_{max} * n$)

The cases c and d are intermediate mechanisms.

case c; gives a bolt force which is less than case d. ($M_c' < M_d'$, so also $Q_c < Q_d$). Case c, however gives a thicker plate than case d ($M_c > M_d$)

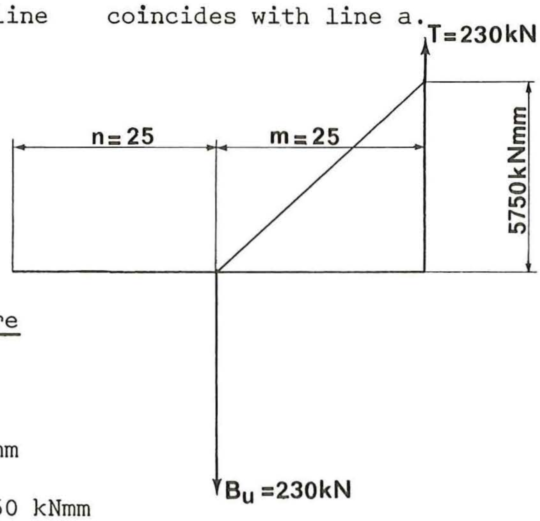
Depending on the available residue $B_u - T = Q$, a special intermediate mechanism can be chosen.

Example (1) case a: limit state of failure

$(M = 4/3\ M_v;\ M' = 0)$ $\left.\begin{array}{l} T = 230 \text{ kN} \\ B_u = 230 \text{ kN} \end{array}\right\}$ $Q = 0$

$m = n = 25$ mm

$Q = 0$ so $M' = 0$ the path of the moment-line coincides with line a.



$4/3\ M_v = T \times m = 230 \times 25 = 5750$ kNmm

so

$B_u = 230$ kN

$M_v = 3300$ kNmm

Example (2) case b: limit state of failure

$(M = 4/3\ M_v;\ M' = 4/3\ M_v')$ $T = 230$ kN

$m = n = 25$ mm

$4/3\ M_v' + 4/3\ M_v = T \times m = 230 \times 25 = 5750$ kNmm

Assume $M_v' = 0{,}8\ M_v \rightarrow M_v = \dfrac{M_v'}{0{,}8}$

$4/3\ (M_v' + \dfrac{M_v'}{0{,}8}) = 5750$ kNmm

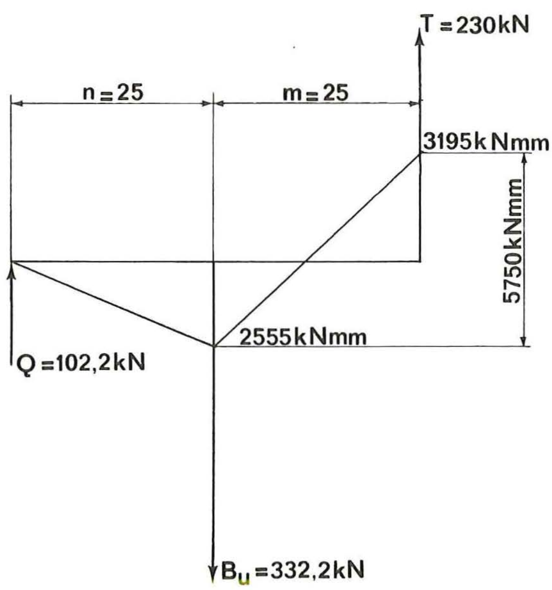
$4/3\ M_v' = 2555$ kNmm

$2555 = Q \times 25 \rightarrow Q = 102{,}2$ kN

$B_u = T + Q = 230 + 102{,}2 = 332{,}2$ kN

so

$B_u = 332{,}2$ kN $M_v = 2390$ kNmm



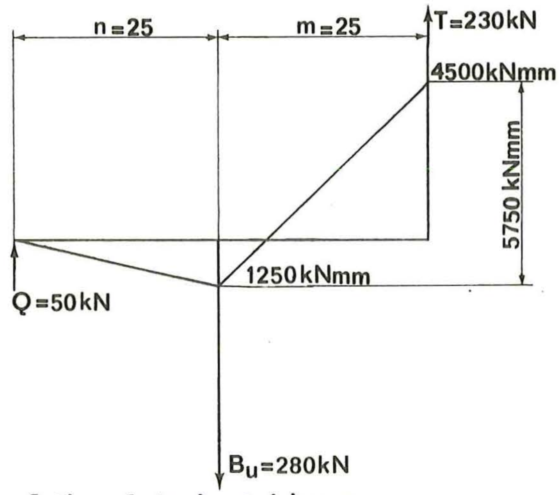
Example (3) case c: (design method) limit state of failure

$(M = 4/3\ M_v;\ 0 < M' < 4/3\ M_v')$ $T = 230$ kN

$m = n = 25$ mm

Applying a bolt with a $B_u = 280$ kN gives the following results:

$Q = B_u - T = 280 - 230 = 50 \text{ kN} \rightarrow M' = 25 \times 50 = 1250$ kNmm



$4/3\ M_v \geq 5750 - 1250 = 4500$ kNmm

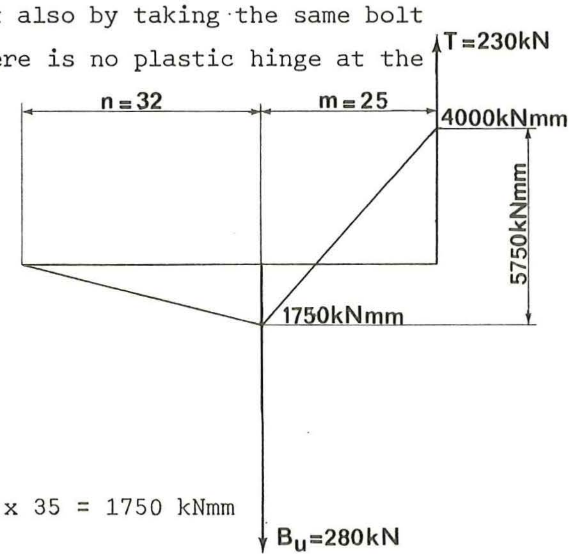
Assume: $M_v' = 0{,}8\ M_v$

than $\quad 4/3\ M_v' = 0{,}8 \times 4500 = 3600$ kNmm

$\quad M' = 1250$ kNmm $\quad$ so $\quad M' < 4/3\ M_v'$

so $\quad$ case c

One can try to obtain a smaller thickness of the plate by taking a larger bolt (larger B_u) see example 2 but also by taking the same bolt (the same B_u) and enlarging size n as there is no plastic hinge at the bolt line in the plate.
This gives:



Example (4): limit state of failure

$T = 230$ kN

$m = 25$ mm

$n = 35$ mm

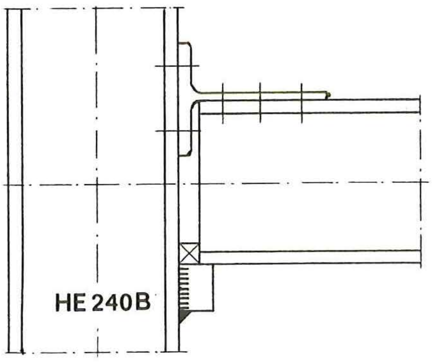
$B_u = 280$ kN

$Q = B_u - T = 280 - 230 = 50 \text{ kN} \rightarrow M' = 50 \times 35 = 1750$ kNmm

$4/3\ M_v \geq 5700 - 1750 = 4000$ kNmm

The moment-line has now been pushed downwards with respect to the values computed in case c of example 3.
The minimum thickness of the plate will be obtained if $M = 4/3\ M_v$ and $M' = 4/3\ M_v'$ (collapse mechanism C).
In this computation it has been assumed that the prying force ,Q, acts on the extreme edge of the plate.
Undoubtedly there are limits for the size n, the extent of which will have to be determined from further tests.
According to Mc Guire (Steel Structures - 1968 page 833) the value ,n, will be no more than: n = 1.25 m.

Example (5) of computation, in which the T-stub flange as well as the column flange can deform.



Let us assume a column HEB 240 with a beam with T-stub connection. The thickness of the T-stub flange is 27 mm and the main dimensions have been drawn in figure 12 on page 27 of the report.

The construction will be made of Fe 37 with $\sigma_v = 240 \ N/mm^2$.

The specification of the bolt is M 16, quality 10.9 with ultimate load F = 157 kN. The question is, which tensile force can be transmitted, taking into account that the column flange can deform too?.

Formulas (1a) and (2a) applied to the T-stub flange give:

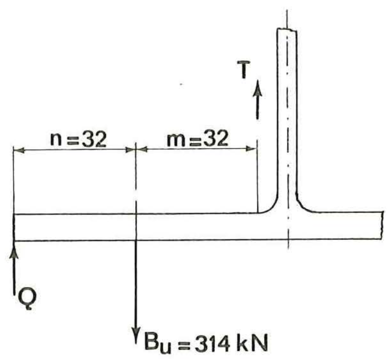
$$M_v = \frac{1}{4} \times 160 \times 27^2 \times 240.10^{-3} = 7000 \text{ kNmm}$$

$$M_v' = \frac{160-36}{160} \times 7000 = 0.775 \times 7000 \text{ kNmm}$$

(1a) $T \times 32 - (314 - T)\, 32 = 7000.4/3$ kNmm

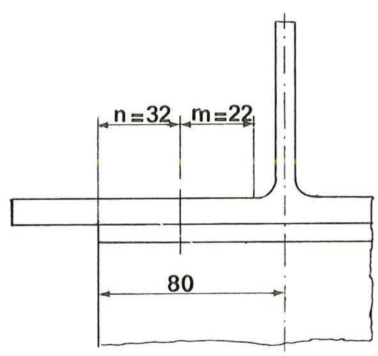
(2a) $T \times 32 = 4/3\, (1{,}775.7000) = 16500$ kNmm

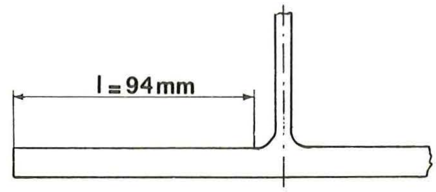
(1a) $\rightarrow T = 303$ kN (2a) $\rightarrow T = 515$ kN



Formulas (1a) and (2a) are now applied to the column flange. The column section is HEB 240 with the dimensions ,m, and ,n, as drawn in the figure. The formula as described on page 19 of the report is used for the computation of an imaginary yielding length, $a + \ell\sqrt{2} = 80 + 94\sqrt{2} = 213$ mm

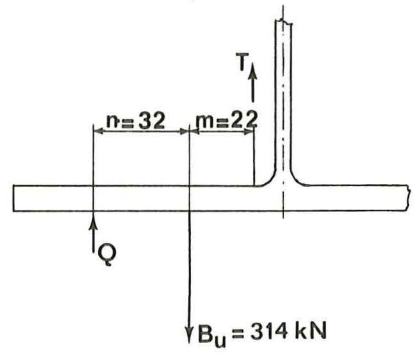
The thickness of the flange is 17 mm.





$$M_v = \frac{1}{4} \times 213 \times 17^2 \times 2.4 = 3690 \text{ kNmm}$$

$$M_v' = \frac{213-36}{213} \times 3690 = 0.83 \times 3690 \text{ kNmm}$$

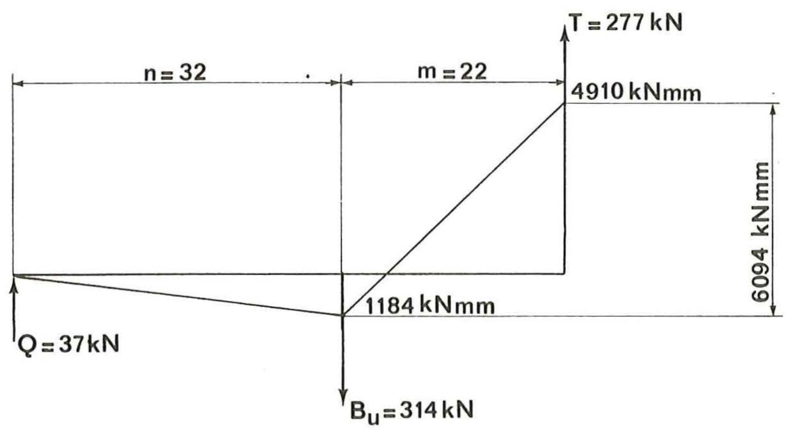


(1a) $T \times 22 - (314 - T)\, 32 = 3690 \times 4/3$ kNmm

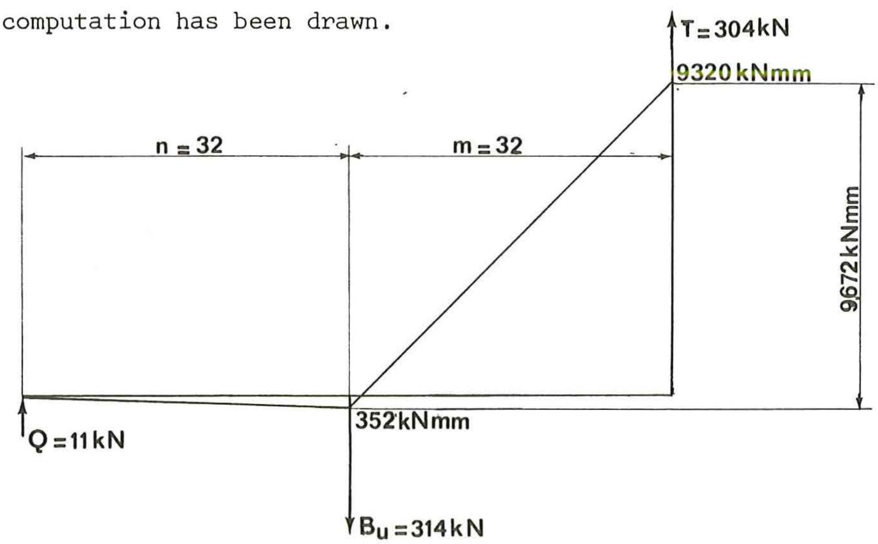
(2a) $T \times 22 = 4/3 \times 1.83 \times 3690$ kNm

(1a) → T = 227 kN (2a) → = 409 kN

From the above-mentioned computations it is found that the column flange is the determining factor because in the optimum situation the tensile force is no more than 277 kN.
The moment-distribution of the column flange at failure of the bolt has been drawn in the following figure.

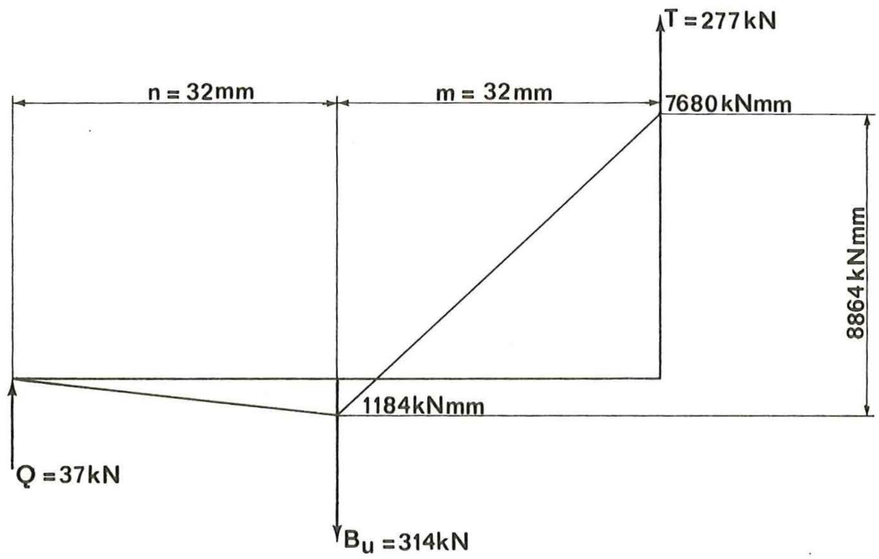


The moment-distribution for the T-stub flange is unknown. In the following figure the optimum state for the T-stub flange according to the computation has been drawn.



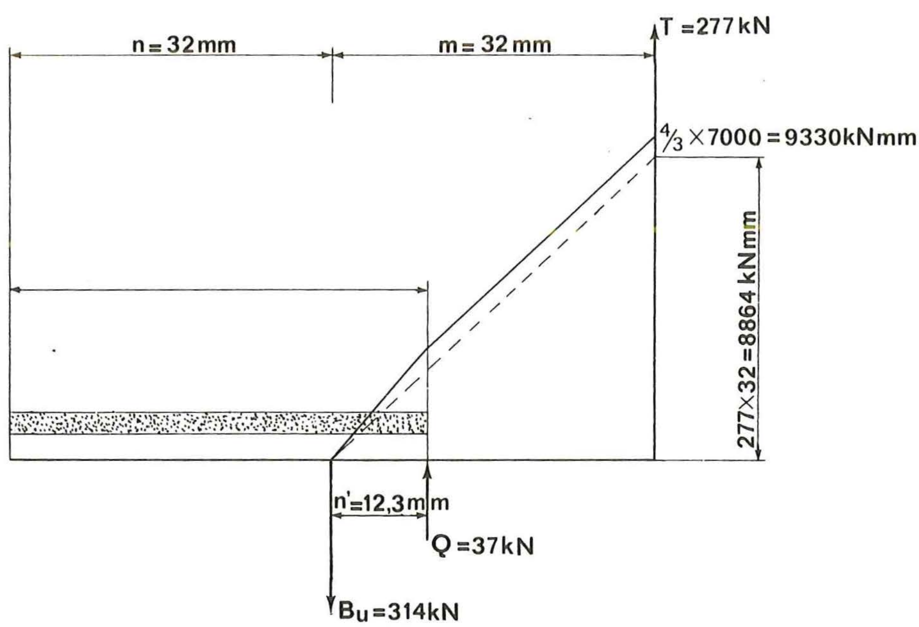
Further explanation of example (5)

It is clear from the computation of the column flange that Q cannot be 11 kN but is 37 kN. Assuming Q = 37 kN acts on the edge of the T-stub flange one gets the moment-distribution as in the following figure. There is no plastic hinge next to the tensile strip.

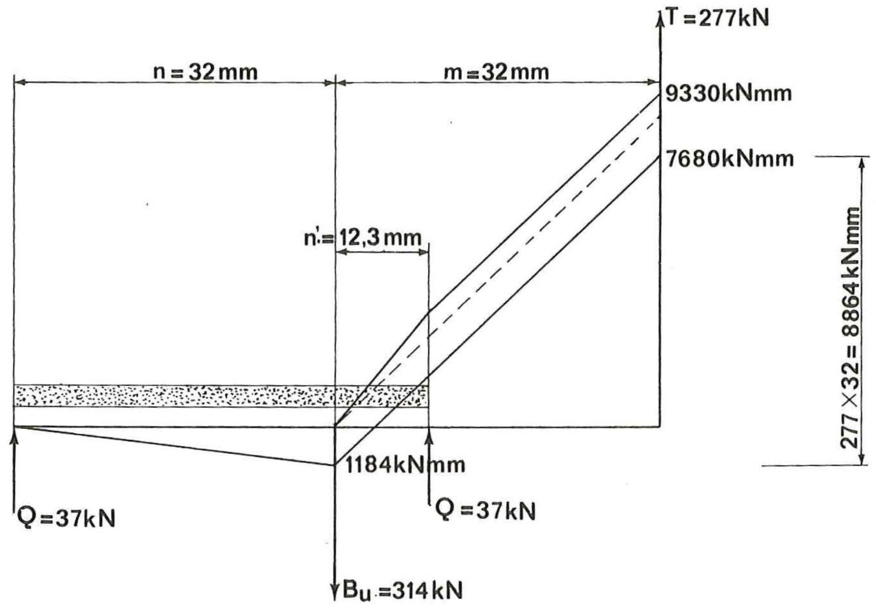


Assuming that, at failure of the bolt, there is a plastic hinge next to the tensile strip gives the moment distribution as drawn in the following figure

$$n' = \frac{9330 - 277 \times 32}{37} = 12.3 \text{ mm}$$



Naturally an intermediate mechanism is possible. Once again the extremes are given in the following figure



The moment-distribution acting in the T-stub flange is not important for the computation.

It is important, however that the connection cannot support more than 277 kN.