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NON LINEAR FINITE ELEMENT ANALYSIS OF THE CONTACT, STRAIN AND STRESS STATES OF A BOLT – NUT – WASHER – COMPRESSED SHEET JOINT SYSTEM

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Abstract

A non-linear finite element model with contact elements was developed to evaluate the contact state of a bolt – nut – washer – compressed sheet joint system.

Applying the proper material law the non-linear behaviour of the members of the joint was studied in term of the clamping force. Based on the FE results the load distribution among the threads in contact and the real preload diagram of the system were evaluated.

To produce the required clamping force at medium strength bolts it is advisable to use heat-treated washers instead of lower strength ones.

Keywords: bolted joint, clamping force, finite element analysis, contact problems.

Introduction

Preloaded bolted joints are widely used to provide safe connection between different parts of a product. There are more and more high strength bolted joint applications with the requirement of the higher preload. To have an economic bolted joint the average stress at the tensile stress area A_s is near to the yield strength [1], [2].

Related to the modern bolted joint design there are some questions to be answered. How can we describe the behavior of the total bolt – nut – washer – compressed sheet system in the range of the higher preload? What element of the system is the critical one? Is the first thread connection always the most loaded one? What is the real load distribution among threads in contact and the real preload diagram if the members of the joint have different strength properties? What is the role of the washer in the range of the higher preload?

In the traditional bolted joint design linear spring models are used [1], [3]. The members of the joint are modelled by tensioned or compressed rods having equivalent diameters and assuming linear elastic material law. This approach provides reasonable results only in the low load range. To evaluate the load distribution in the elastic-plastic range [4] an optical measurement procedure is introduced.

The current finite element analysis follows different non linear material laws of the members and the real geometry is studied using frictionless contact elements. (This approach produces an error proportional to the magnitude of the coefficient of friction.) [5]. The analysis covers the strain and stress analysis in a bolted joint in case of different materials, studies the role of the lower strength and heat-treated washers, furthermore evaluates the real preload diagram of the bolted joint system.

2. Describing the Analysed Bolted Joint

The sizes of bolts at the analysed models (*Fig. 1*) are M16×75 and M16×80. The fit of the threads is 6H/6g. The total thickness of the compressed sheets is 60 mm. The surfaces of the two sheets are parallel ideal planes.

Based on the structural model the following cases are examined:

M1. bolt and nut made of material 5.8 with lower strength washer (LSW)
M2. bolt and nut made of material 5.8 with two heat-treated washers (HTW)
M3. bolt and nut made of material 8.8 with lower strength washer (LSW)
M4. bolt and nut made of material 8.8 with two heat-treated washers (HTW)

The upper part of *Fig. 1* relates to cases M2. and M4., while below the symmetric line relates to cases M1. and M3.

The materials of the individual members are as follows:

sheets	Fe 275	$(R_{eH}/R_m = 235/380$ MPa)	
bolts	5.8	$(R_{eL}/R_m = 400/520$ MPa)	(lower strength)
	8.8	$(R_{p02}/R_m = 640/800$ MPa)	(medium strength)
nuts	5.		(lower strength)
	8.		(medium strength)
washers	Fe 235	$(R_{eH}/R_m = 225/340$ MPa)	(lower strength)
	C 45	$(R_{p02}/R_m = 420/800)$	(heat-treated)

where R_{eL} lower yield strength,
R_{p02} proportional limit,
R_m ultimate strength.

The preload force was increased up to and beyond FY (*Fig. 13*) during the non-linear elastic-plastic analysis. At this load level, assuming homogeneous tensile stresses, we have reached the yield strength at the ten-

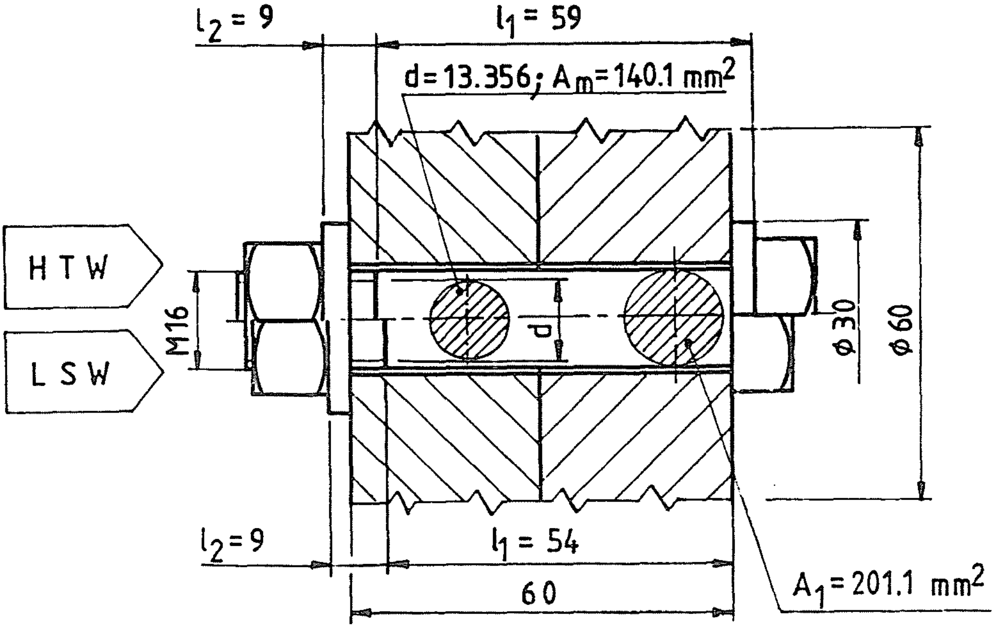

Fig. 1.

sile stress area (A_s). In the technical literature there are different allowable working load levels (based on homogeneous stress calculation) depending on the operating conditions. The load level of 0.55 R_m and 0.62 R_m (see *Fig. 13*) corresponds to the average and maximum preload of a general purpose bolted joint [1]. Considering the operating conditions there are circumstances when the working load in the bolted joint may reach F_{proof}. (F_{proof} is the highest tensile force they could withstand without taking any permanent deformation [1]).

3. Stiffness Calculation of the Bolted Joint Based on Linear Spring Models

The following equations represent the traditional analysis of the bolt – nut – washer – compressed sheet system [1], [3]. The total stiffness K_T of bolt, nut and washer :

Cases M1 and M3 $\quad \frac{1}{K_{T1}} = \frac{1}{K_{B1}} + \frac{1}{K_N} + \frac{1}{K_{W1}},$

Cases M2 and M4 $\quad \frac{1}{K_{T2}} = \frac{1}{K_{B2}} + \frac{1}{K_N} + \frac{2}{K_{W2}}.$

The bolt stiffness K_B [3], following the notation of *Fig. 1*:

$$\frac{1}{K_B} = \frac{1}{E}\left[0.4\frac{d}{A_1} + \frac{l_1}{A_1} + \frac{l_2}{A_m} + 0.4\frac{d}{A_m}\right] .$$

The stiffness of the nut K_N and washer K_W is directly calculated from the geometry. The stiffness of the compressed sheets K_J was calculated according to MEYER – STRELOW [3], where the equivalent cross-section is $A_C = 630.02\ \mathrm{mm}^2$.

The calculated stiffnesses:

$K_{B1} = 5.2828 \cdot 10^5$ N/mm, $K_{B2} = 4.9718 \cdot 10^5$ N/mm, $K_N = 4.3982 \cdot 10^6$ N/mm,
$K_{W1} = 3.3215 \cdot 10^7$ N/mm, $K_{W2} = 2.4912 \cdot 10^7$ N/mm, $K_J = 2.2051 \cdot 10^6$ N/mm,
$K_{T1} = 4.6503 \cdot 10^5$ N/mm, $K_{T2} = 4.3122 \cdot 10^5$ N/mm.

The preload diagrams based on these stiffnesses are shown with thin lines in *Fig. 13*.

4. The Finite Element Model of the Bolted Joint

To model the bolt – nut – washer – sheet system 4 node axisymmetric elements are used. Frictionless contact elements are located between the threads in contact, on both sides of the washers and between the bolt's head and the sheet in the following numbers:

threads:	$6 \times 5 = 30$	elements,
washer:	$11 + 17 = 28$	elements,
bolt's head:	11	elements.

Fig. 2 shows the axisymmetric finite element model for cases M2. and M4., while the enlarged FE mesh in the vicinity of the bolt, nut and washer is shown in *Fig. 3*.

The clamping force is introduced as distributed load over the cross-section in the middle of the shank of bolt (the bolt was cut into two parts). The clamping force 'flows' through the nut, washer, sheets and bolt's head, producing a closed force flow.

The material laws are linear static and strain hardening ones according to the given yield strength of each member. The tangent modulus of each material in the strain hardening range is $E' = 500$ MPa.

The boundary conditions are activated at the common surface of the compressed sheets (*Fig. 1*) allowing only radial displacement.

To solve this problem the non-linear module of COSMOS/M EXPLORER and the displacement control algorithm were used. This algorithm could evaluate the fairly high plastic strains in the lower strength washers.

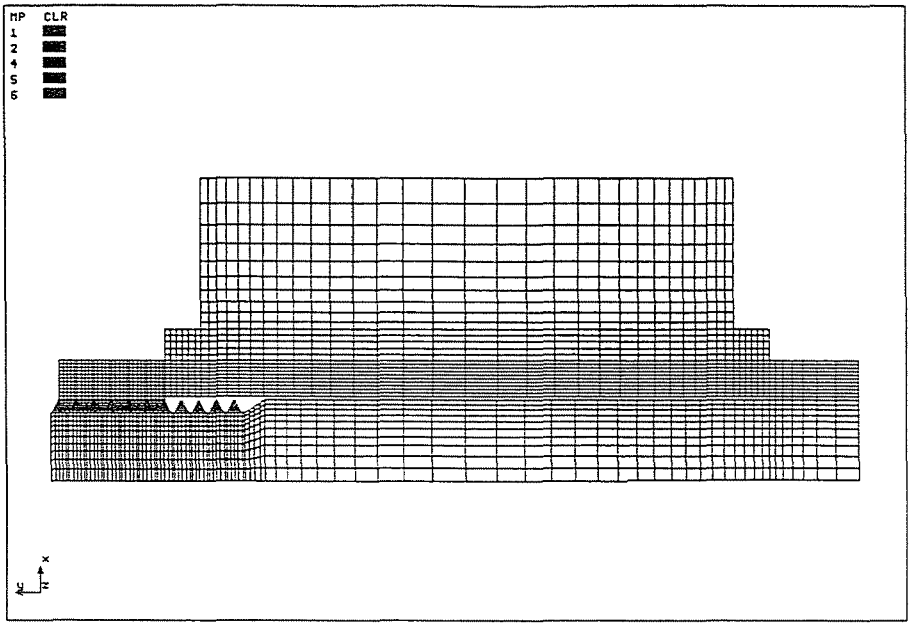

Fig. 2.

5. The Stresses and Strains in the Bolted Joint

5.1 Bolted Joint with Lower Strength Bolt (5.8) and Lower Strength or Heat-Treated Washers

The stresses and strains of a lower strength bolt and nut are shown in *Figs. 4, 5, 6* and *7* at 0.62 R_m load level. By the help of the deformed shapes the local sliding between the threads and the smaller radial sliding of the washer can be followed in *Fig. 4*. The von-Mises equivalent stress distribution shown in *Fig. 4* explains the 'force flow' producing overloading between the first threads near to the washer, furthermore local overloading in the bolt next to the washer. Altogether these results show small plastic zones in the bolt and the nut.

The stress levels are lower in the washer and compressed sheets due to the lower yield strength. In *Fig. 5* the high stresses in the vicinity of the bolt's head are shown.

The plastic behaviour of the analysed bolted joint system is shown in *Figs. 6* and *7*. In the black areas the total equivalent strains (definition

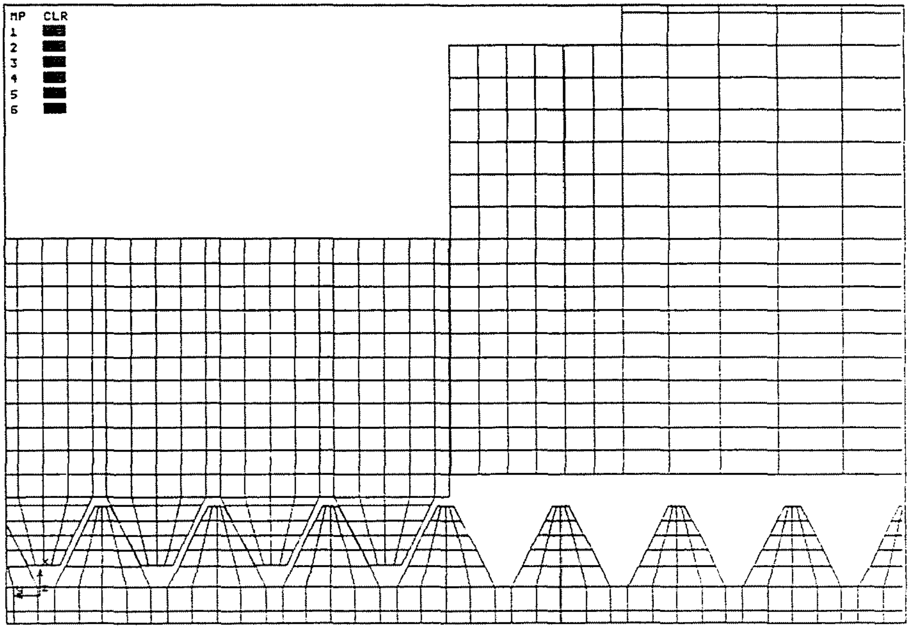

Fig. 3.

in [6]) are greater or equal to 0.002 (0.2 %). This equivalent strain level represents the border of plastic zones of the bolt and the nut, because the yield strength of them is 400 MPa. At this load level there are smaller plastic zones in the vicinity of the threads and in the nut next to the washer. The plastic zone in the washer is slightly greater than the black area in *Fig. 6* due to the lower yield strength (235 MPa) of the washer.

The heat-treated washer in *Fig. 7* remains totally in elastic range at 0.62 R_m load level.

5.2 Bolted Joint with Medium Strength Bolt (8.8) and Lower Strength or Heat-Treated Washers

Let us use the same load level of 0.62 R_m. In *Fig. 8* the black areas represent the total equivalent strains, that is greater or equal to 0.0032. (Yield strength is 640 MPa). The extent of the plastic zones in the vicinity of the threaded zones is almost the same as in *Fig. 6* because the load level is proportional to the higher ultimate (or yield) strength.

In the lower strength washer at the same time there is a big plastic zone with the maximum equivalent strain of 0.029 (2.9 %). The huge

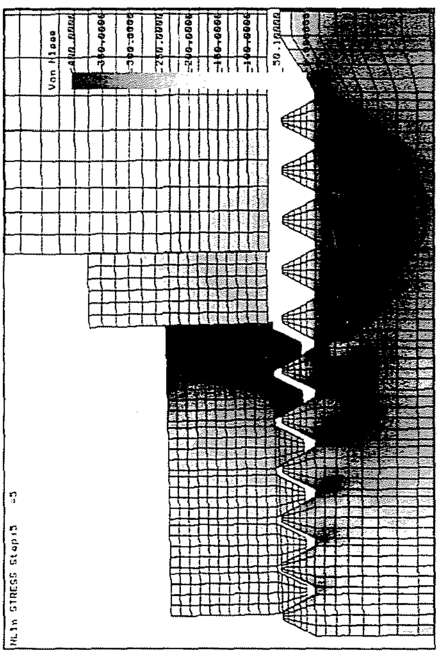

Fig 4.

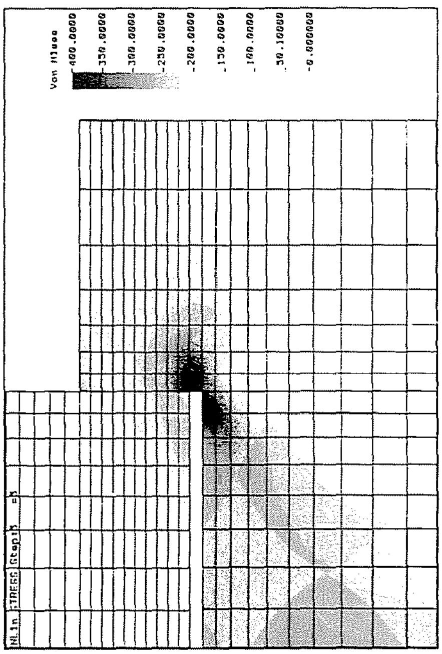

Fig 5.

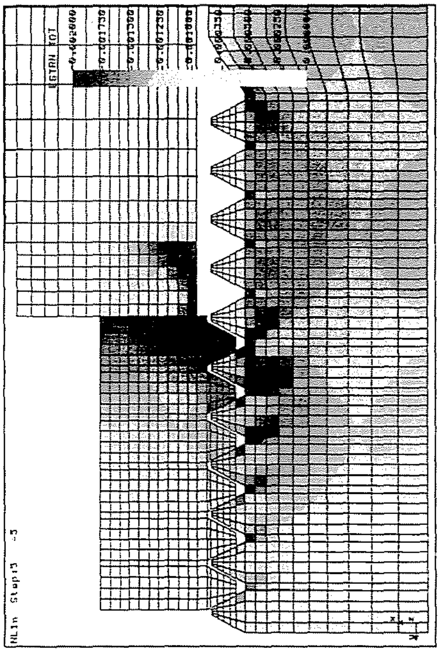

Fig 6.

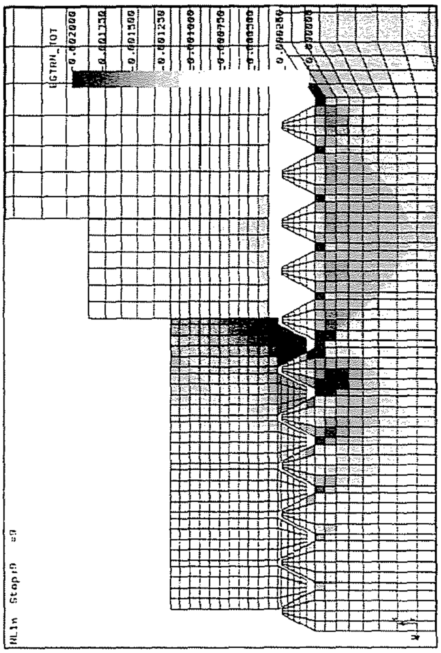

Fig 7.

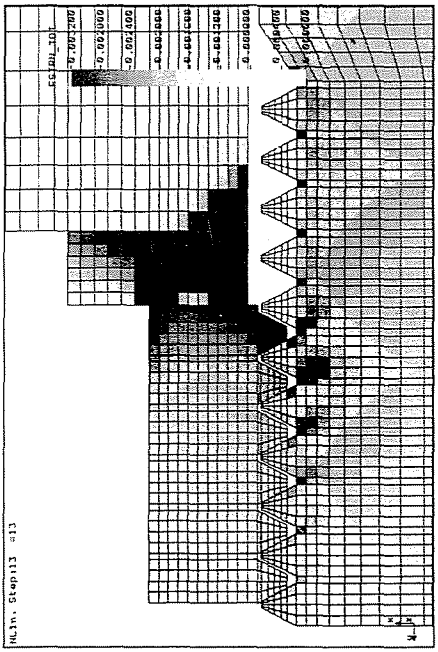

Fig 8.

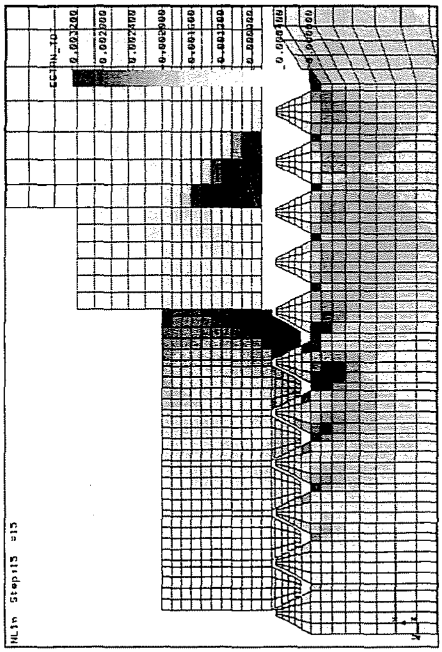

Fig 9.

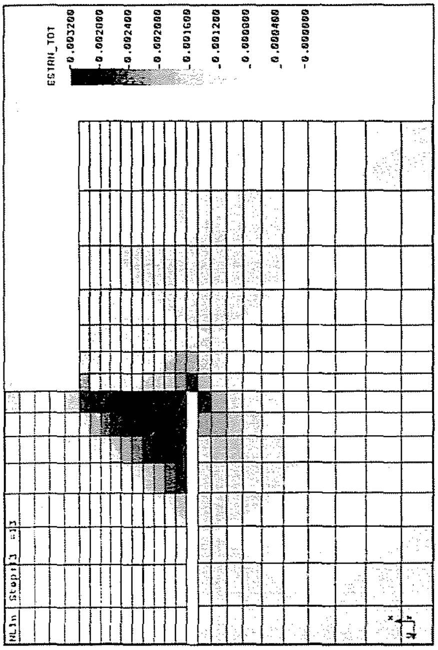

Fig 10.

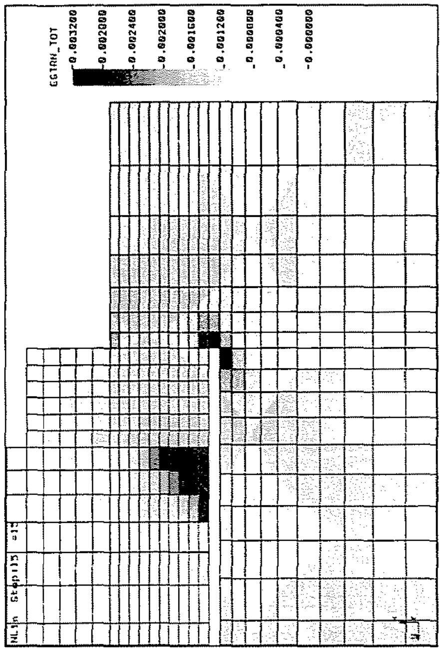

Fig 11.

plastic zone basically modifies the stiffness of the washer and consequently the stiffness of the whole system.

The plastic zones in the compressed sheets are smaller. In *Fig. 10* near to the bolt's head we have a bigger local plastic zone in the compressed sheet with the maximum equivalent strain of 0.006 (0.6 %). This plastic zone modifies the stiffness of the sheets and consequently the stiffness of the whole system.

The role of the two heat-treated washers is shown in *Figs. 9* and *11*. None of the washers enters into the plastic state and the load is transmitted via a larger surface.

6. Load Distribution among the Threads in Contact

Let us analyse thread by thread the force system transferred through the contact elements between the threads in contact. In *Fig. 12*, following the order of the finite element mesh, the load distributions for cases M1 and M3 are shown for both materials. The numbers represent the load portion related to the ultimate strength. The first series of curves (from left to the right) characterise the behaviour of the threads in the elastic range, while the next curves show the effect of the plastic zones near to the most loaded threads.

According to the elastic load distribution (first curve in *Fig. 12*) the load on the first thread is about the double of the load of the last thread contrary to the difference of 3 to 4 given in a textbook published earlier [7]. To check this model for one elastic calculation we fixed the nut surface (next to the washer) in axial direction, while the radial displacement was allowed. The results drawn by dotted lines show a good agreement to the earlier results.

Let us study the load distribution in higher load range. Near to the load level equivalent to 60 % of the ultimate strength of the bolt the most loaded thread cannot transfer higher load, due to the increasing plastic zones, while the following threads can do it. At about 70 % of the ultimate strength the second thread cannot transfer higher load any more. The third thread has the same performance above the load equivalent to 80 % of the ultimate strength.

7. The Preload Diagram of the Bolted Joint

Fig. 13 shows the preload diagram for the studied four cases. Thin lines denote the preload diagram at level of 0.55 R_m obtained by linear spring model [1].

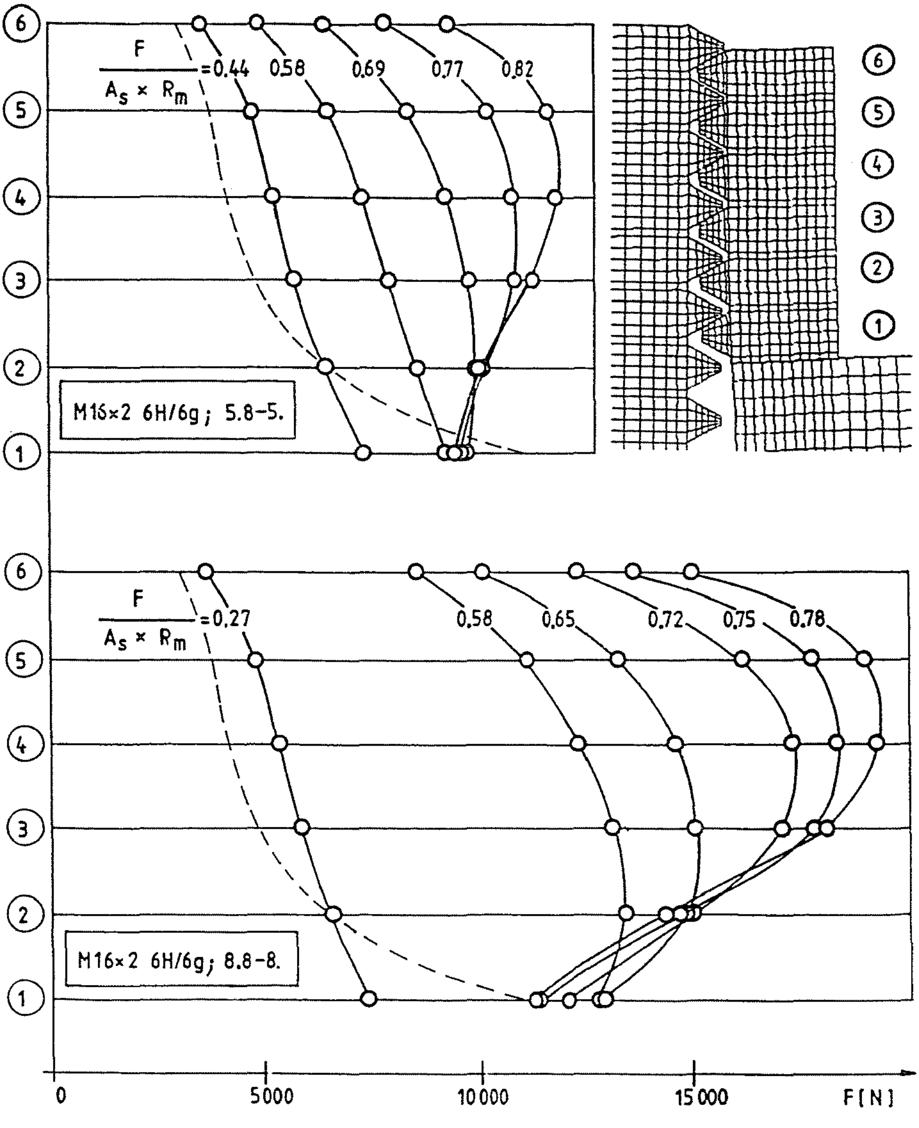

Fig. 12.

Considering material 5.8 both the lower strength (LSW) and the heat-treated washers (HTW) have almost the same stiffness behaviour. There are bigger differences considering material 8.8. In case M3. (8.8+LSW) at about preload level of 0.55 R_m there are huge plastic zones in the lower strength washer and the compressed sheet (near to the bolt's head). *In this way the better material of the bolt and nut cannot be utilized, the re-*

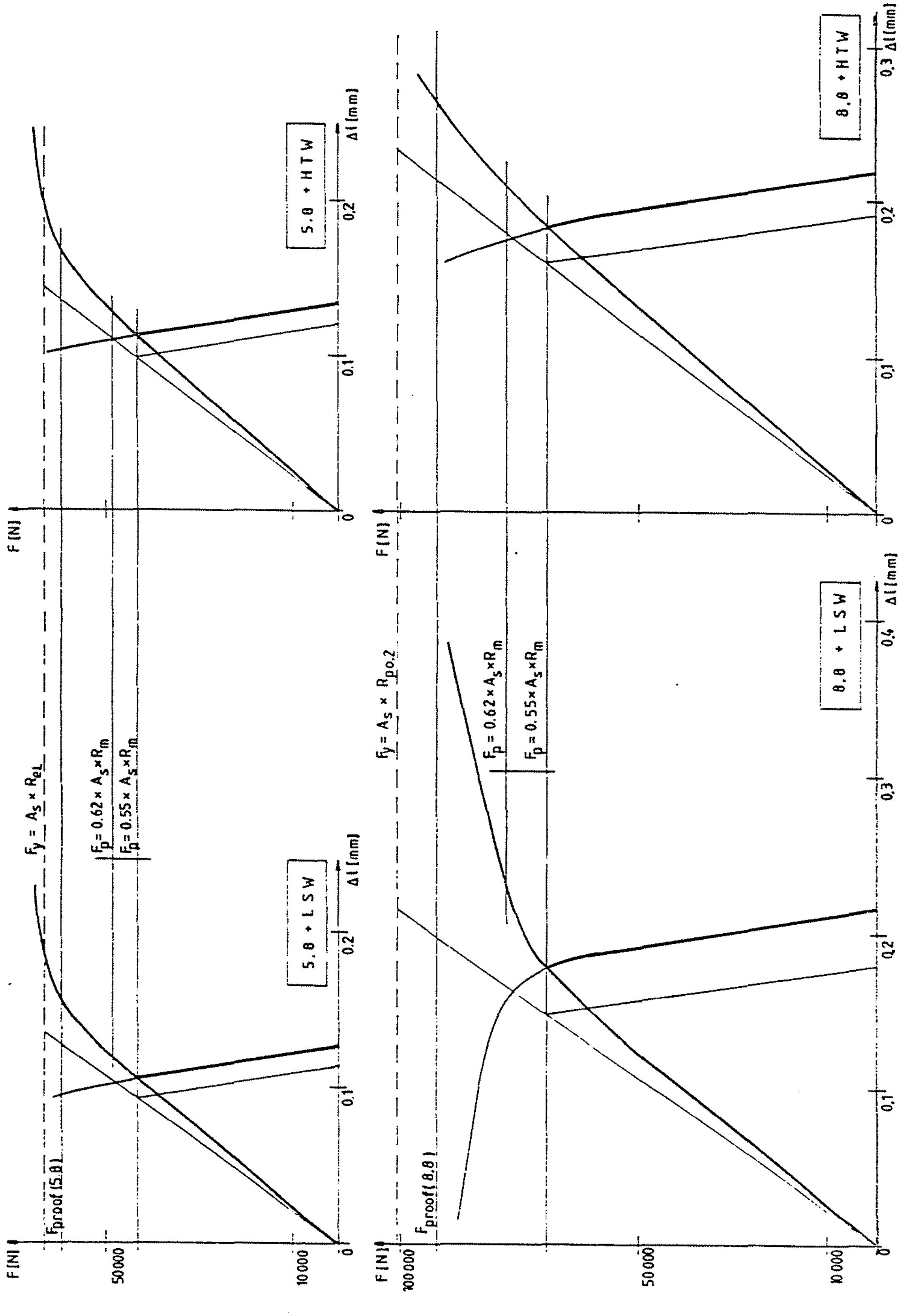
F (N)
50000
10000
0
0.1
0.2
Δl (mm)
F (N)
100000
50000
10000
0.3
0.4
5.8 + LSW
5.8 + HTW
8.8 + LSW
8.8 + HTW
F_y = A_S × R_eL
F_p = 0.62 × A_s × R_m
F_p = 0.55 × A_s × R_m
F_proof (5.8)
F_y = A_S × R_p0.2
F_proof (8.8)

Fig. 13.

quired preload cannot be achieved. Two heat-treated washers can solve this problem. In case M4. (8.8+HTW) the preload diagram is almost linear up to the range of the yield strength so this preload level may be achieved.

8. Conclusions

The non-linear axisymmetric model with contact elements is suitable

- to analyse the bolted joint having parts with different strength properties,
- to find the plastic zones,
- to obtain the load distributions among threads in contact,
- to determine the real preload diagram of the bolted joint system.

To be able to increase the preload of a bolted joint system having medium strength bolts and nuts it is advisable to use heat-treated washers.

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Gyula Strommer

Es hätte ein Festtag für Professor Gyula Strommer werden sollen, und ist doch ein Trauer- und Gedenktag geworden. Herr Prof. Strommer ist am 28. August von uns gegangen, nachdem ein unerbittliches Schicksal ihn schon monatelang an das Krankenbett gefesselt hatte.

Wer das Glück hatte, Herrn Strommer näher gekannt zu haben, hat viel von ihm lernen können. Seine wissenschaftlichen Leistungen, vor allem auf dem Gebiet der Axiomatik, haben ihn weit über die ungarischen Grenzen hinaus bekannt gemacht. Wer erinnert sich nicht an seine brillianten Vorträge, bei denen er in fehlerlosem Deutsch seine Ideen vortrug, und dabei in ruhigen, wohlgemessenen Schritten vor der Tafel oder Leinwand auf- und abwanderte. Aber auch seine Lehrbücher haben ihm verdienten Ruhm eingebracht. Und Tausende der heute aktiven ungarischen Ingenieure sind durch ihn in die Gedankenwelt der Darstellenden Geometrie eingeführt worden.

Aber auch seine menschliche Seite war vorbildhaft. Er war voll freundlicher Vornemheit und Korrektheit. Er wußte sehr wohl, ehrliches wissenschaftliches Bemühen von Scharlatanerie zu unterscheiden. Es fehlte ihm auch nicht ein Hang zu leicht ironischer Selbstkritik. Aber er war auch oft voll Lebensfreude, und man konnte viel lachen mit ihm, obwohl er in seinem Leben auch mit so manchen Härten fertig werden mußte.

Der allzu frühe Tod von Prof. Gyula Strommer schmerzt. Ein Grandsegnieur der Geometrie hat uns für immer verlassen. Er wird uns fehlen.

Hellmuth Stachel im Namen der Tagungsleitung
der Gedenktagung Konstruktive Geometrie
Balatonföldvár 11–15 September 1995.