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APPROXIMATE COMPUTATIONAL METHOD OF FLANGE PLATE CONNECTIONS IN ELASTIC RANGE

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Abstract

At the Department of Steel Structures of TUB experiments and numerical analyses were carried out with flange plate connections. This paper is to present the numerical analysis of one of those specimens. The experimental and numerical results are compared in order to refine the approximate method, with the main aims to adapt the process usual is mechanical engineering practice and to give a recommendation for analysis of flange plate connections with prestressed bolts.

Keywords: tension bolt, end-plate, flange plate.

1. Introduction

Research on tension bolted connections started in 1976 at the Department of Steel Structures of TUB. Investigations were focused on tension T-connections of beams and frames (HALÁSZ – IVÁNYI, 1979). A great impetus was given by the latter researches to experimental and numerical analyses. Some connections were tested for dynamic loads for practical purposes. In order to avoid the disadvantages of tension bolted connections – bolt force relaxation due to loading and unloading and significant opening of end-plates — a flange plate was applied in beam-to-beam connections (SZABÓ, 1987, MOLNÁR, 1988, SZABÓ, 1990). The experimental analysis of flange plate connections was followed by numerical analysis (MÁTÉ, 1993) developed by SZABÓ and carried out by LUSAS finite element system (FEA LTD). The main aims are to adapt regarding process of mechanical engineering practice and to give a recommendation for analysis of flange plate connections with prestressed bolts. We note that flange plate connections are applied, first of all, in the beam-to-column joints. In the approximate computational method the web bolts take the shear, and the flange bolts (acting in shear) resist the moment. The flange plate forces are equal to moment divided by distance from centreline of compressed flange-to-flange plate.

2. Specimen Selection for Finite Element Program

Application of finite element analysis needs a model fitting best for the structure, for mesh, taking the material properties into consideration, and granting the external loadings. The behaviour of the structure is modelled and the results are checked against the experimental data.

The basis of the work was a beam with flange plate and end-plates with HSFG bolts subjected to tension, bending and shear tested in MOLNÁR (1988), as seen in *Fig. 1.* The study was divided into two subprograms (I and II) because there were two beams with connections. The thickness of the end-plate (V_1), diameter and number of the bolts in the flange plate were constant. The diameter and prestress of the bolts in the end-plate, the thickness of the flange plate were changed.

The beams were examined:

- with prestress in the end-plate bolts
- without prestress in the end-plate bolts
- with prestress in the end-plate bolts, with another flange plate
- without prestress in the end-plate bolts, with the preceding flange plate
- with test up to the failure of the beam or connection.

From the first to fourth loading cases the structures were examined in elastic range, in the fifth case in plastic range.

Keeping the main goals in mind, the following parameters were measured:

- loading
- strains by mechanical Pfender instrument and strain gauges 300 mm of the connection on both sides, including flange plate
- bolt forces in the end-plate bolts by special dynamometer
- in-plane deflections by inductive transducers at the end cross-section of the beam, at mid-span and at the connection.

A lot of experimental results are given in MOLNÁR, (1988). From experimental data, the distribution of normal and shear stresses in the surroundings of the connection are emphasised in SZABÓ, (1990). Normal stresses were observed in every element of the beam, while shear stresses concerned only the web. One of the measured normal stress distributions (σ_x) and normal stresses calculated on the basis of the elementary strength theory were compared near the connection. The stress distribution of joint section — where specified tension forces were applied either in the flange plate or bolt – is in good agreement with σ_x normal stresses calculated on the basis of the elementary strength theory. This fact is shown in *Fig. 5*

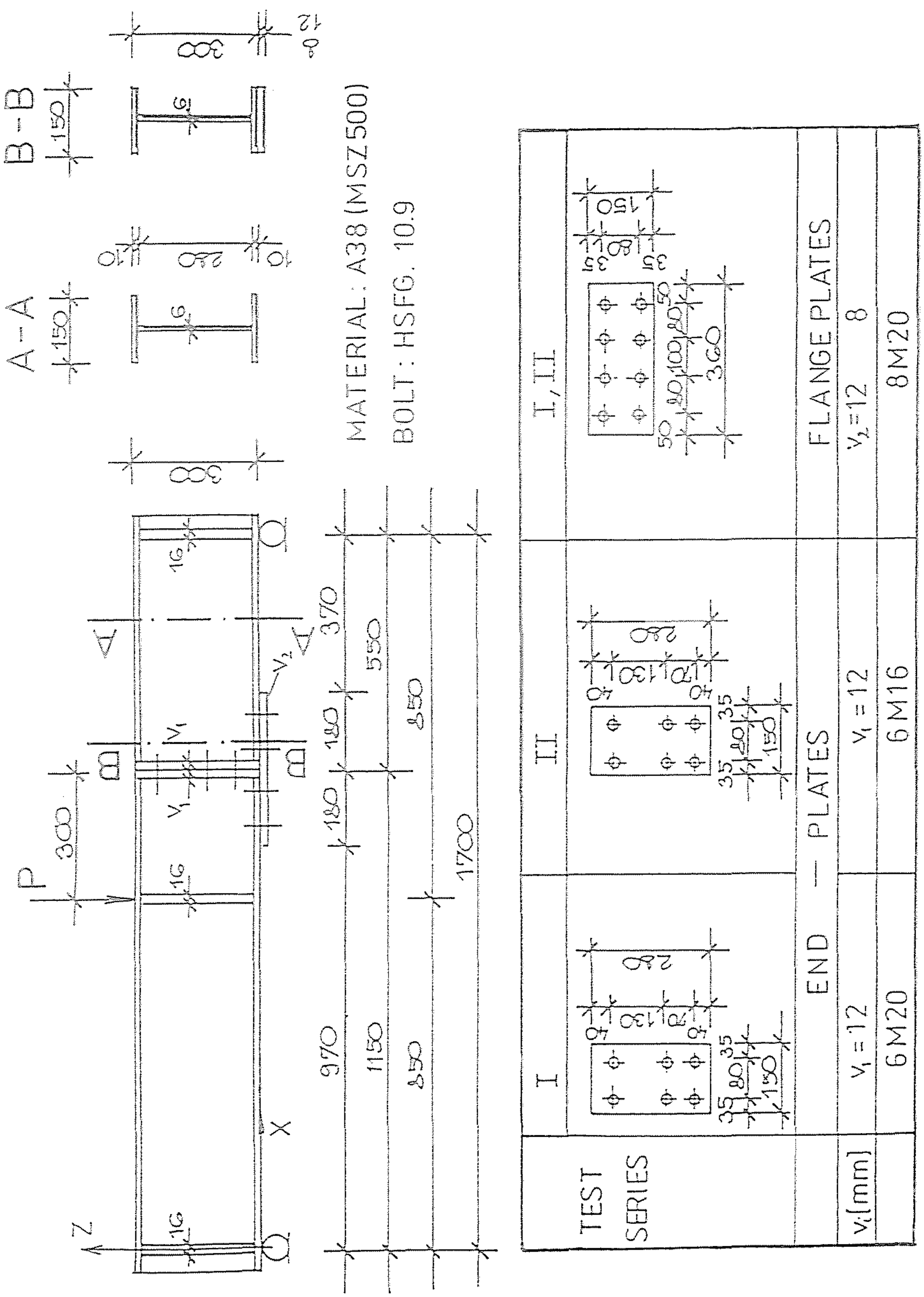

Fig. 1. Test program of flange plate connections

together with the results of the finite element analysis. The elementary strength calculation was carried out regarding the upper and lower flange, web and flange plate when determining the elastic section modulus. The prestressed bolts and the flange plate caused continuous beam behaviour in respect of moment resistance and rotation stiffness. The beam was loaded by a hydraulic jack working in the mid-span cross-section as a patch load.

3. The Finite Element Model

In the second paragraph the experimental analysis and the load cases were shown. The finite element model was selected for the first load case where the prestressed (applying specified tension force) HSFG bolts (M20) were in the end-plate and the thickness of flange plate was 12 mm. The mesh was developed by means of the graphical pre- and postprocessing system MYSTRO of LUSAS, symmetry of the structure was utilised, that is why only the half beam was examined using three-dimensional solid continua with 8 and 6 points. The HX8M and PN6 (*Fig. 2*) solid continua have 3 freedoms in nodes (u, v, w). The mesh was formed at the simpler places – by elementary strength theory – with relatively large elements, while in the surrounding of the connection of HSFG bolts the mesh was refined. Between the contact surfaces of the end-plate slidelines were placed (SZABÓ, 1995). The diameter of bolt holes was 21 mm. The peak diameter of nut and bolt head was identical to the diameter of the washer (both elements were contracted by geometrical aspect). This connection with the mesh can be seen in *Fig. 3*. Since the half of the beam was examined, the displacement perpendicular to the axis x of the beam is restrained. Elastic material properties were assumed. The prestresses of the HSFG bolts in the end-plate are modelled as a temperature load acting on the bolts calculated from the specified tension force. The temperature difference was calculated from the following formula:

$$\Delta t = \frac{F_0}{A\alpha E},$$

where
F_0 = specified tension force
A = shank cross-section of the bolt
α = the coefficient of thermal expansion
E = Young's modulus

The stresses can be compared within experimental and numerical analyses and elementary strength theory having linear isotropic material properties.

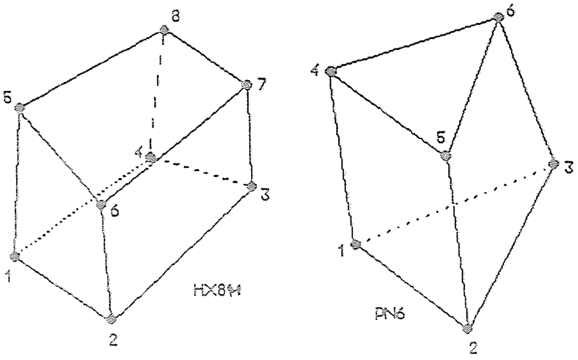

Fig. 2. HX8M and PN6 solid continua

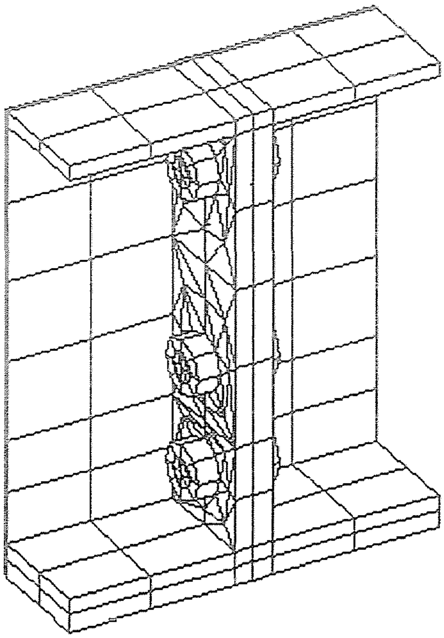

Fig. 3. Flange plate connection with mesh

In order to provide compatibility, either nodes of the bolt head and nut or end-plate constraint equations were connected.

4. Comparison of Results of Numerical and Experimental Analyses

As mentioned, the numerical and experimental analyses were carried out in elastic range. In the numerical analysis two force values (50 kN and 200 kN) were applied in the mid-span. The values of force were selected so that the first caused clear elastic state in the beam, while the second was on the upper limit of elastic range. The stress distribution σ_x of the web (applied load 50 kN) can be seen in *Fig. 4* in form of contour plots. MYSTRO may be used to process results on sections taken arbitrarily through any analysed model.

Two types of sections were taken in the investigations:

- Line sections
- Slice sections

For each line section taken, two data sets were created. The first contained the distance as measured along the drawn line, the second comprised the associated numerical values. Four line sections on the web contour (applied load 50 kN) were taken (see *Fig. 4*). Notice that the height of the compressed zone approximately equals the half of that of the original beam. A line section on the web contour (applied load 200 kN) was also taken at the second vertical mesh (*Fig. 5* left-hand side) where the normal stresses σ_x can be seen due to numerical, experimental and elementary strength analyses. The maximal difference between the experimental stresses and LUSAS data and stresses of elementary strength theory was 30 $\mathrm{N/mm^2}$ and 25 $\mathrm{N/mm^2}$, respectively. Surprisingly in the extreme fibre of the beam the values of LUSAS were almost equal to those of the elementary strength theory. Notice that the above mentioned normal stress distributions (experimental and numerical) originated from applied external force when the end-plates were relatively thin (12 mm). If we took design rules or yield line theory for restrained parts of end-plates, we would get good coincidence of normal stresses (by numerical, experimental and elementary strength theory).

At last the shear stress τ_{xz} distribution of the web is shown in *Fig. 6* (applied load 50 kN). This shear stress distribution originating in the end-plates is interesting from the point of view of small range (*C* and *D* contours). That means the largest part of the shear stress is carried by the flange plate. There seems to be a contradiction between approximate method (see Introduction) where the web bolts take the shear and the flange bolts (acting in shear) resist the moment and the results. The above mentioned phenomenon corresponds with the experimental analysis. Finally, this fact is on the safe side.

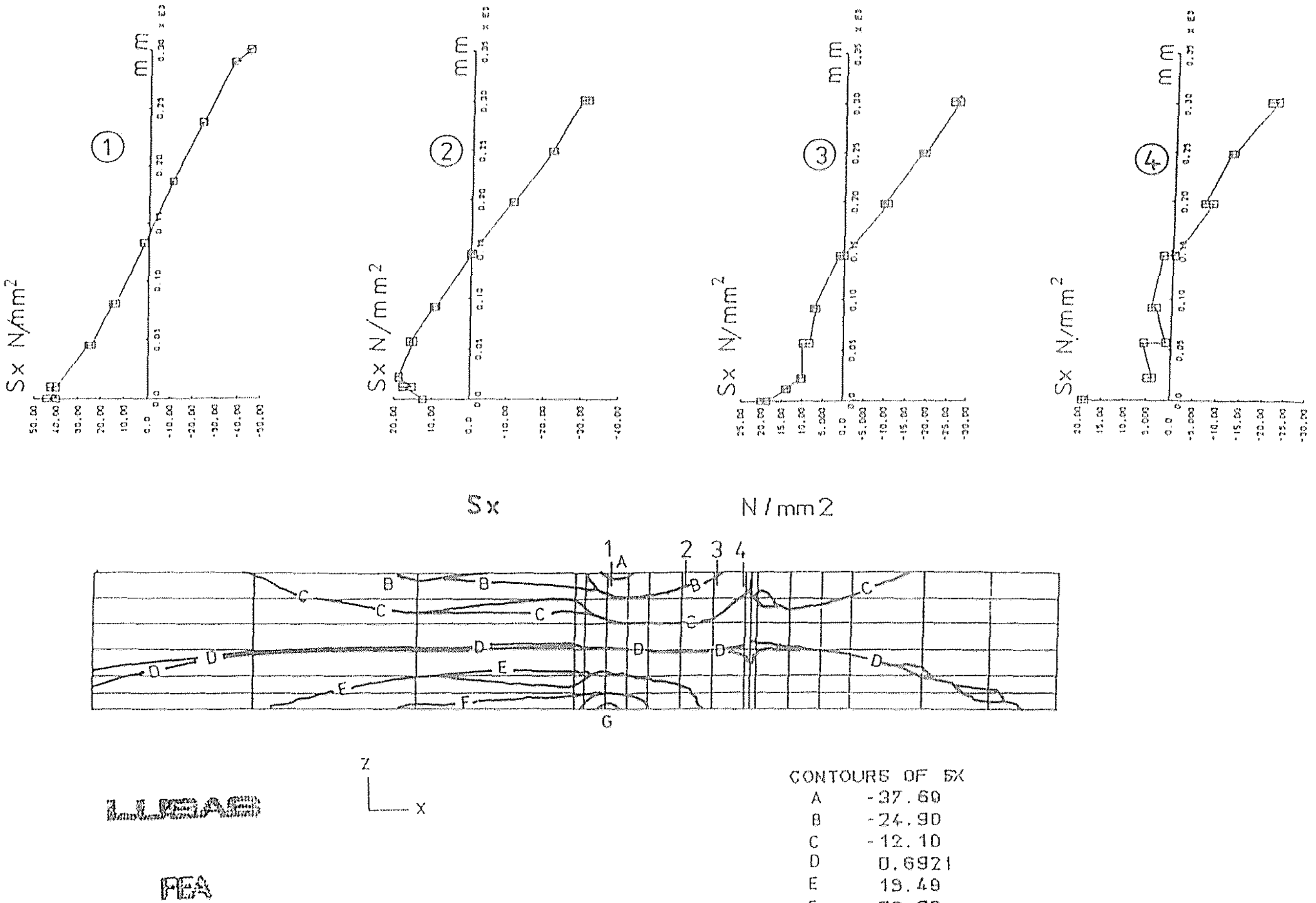

Fig. 4. Stress distribution σ_x of the web (applied load 50 kN)

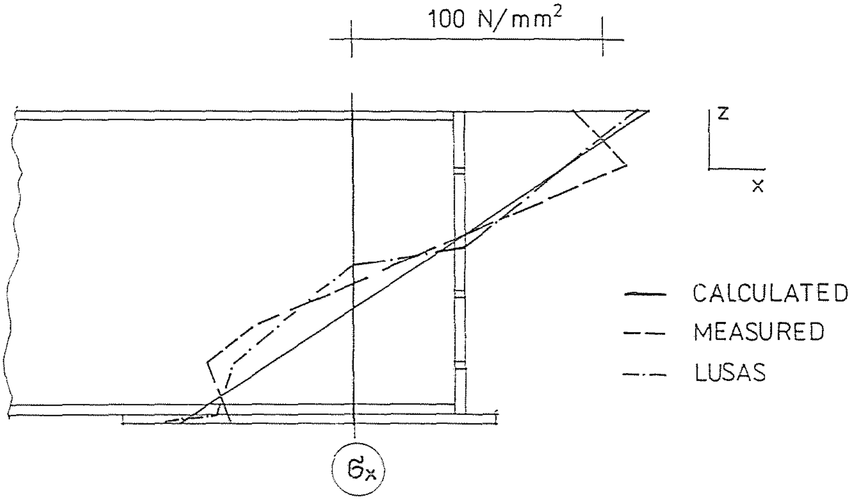

Fig. 5. Normal stress σ_x in numerical, experimental and elementary strength analyses

The most difficult part of the work was modelling HSFG bolts prestressed and loaded by internal forces due to external force. In the middle part of the bolt shank uniform stress σ_x distribution was given, but was not in the bolt head and the nut. Refining the bolt mesh is needed in order to give more information about the distribution of bolt forces. In the experimental analysis in one of the end-plate bolts 15 kN increase occurred which is about 15% of the specified tension force.

5. Recommendation of Designing Flange Plate Connection in Elastic Range

Force in prestressed fastener, widely used in mechanical engineering practice (FISHER – STRUIK, 1973) can be seen in *Fig. 7* now applied under static loading.

Here

F_t = forces in the prestressed HSFG bolt and precompressed end-plates
F_{cs} = force in the prestressed HSFG bolt
F_0^e = prestress of HSFG bolt
Δl = strain in the bolt or compression of end-plate
Δl_{cs} = strain of HSFG bolt
Δl_k = compression of end-plates
$F_{\ddot{u}}$ = internal load due to external load of the beam
ΔF = bolt force difference

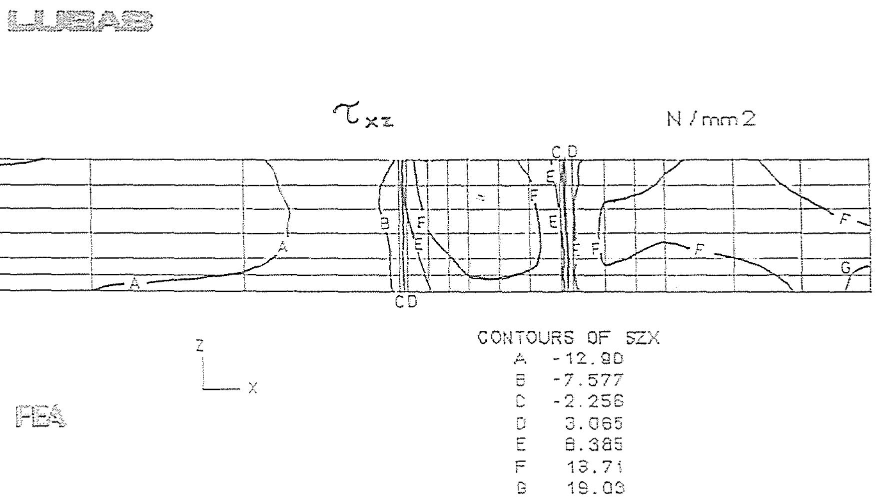

Fig. 6. Shear stress τ_{xz} distribution of the web

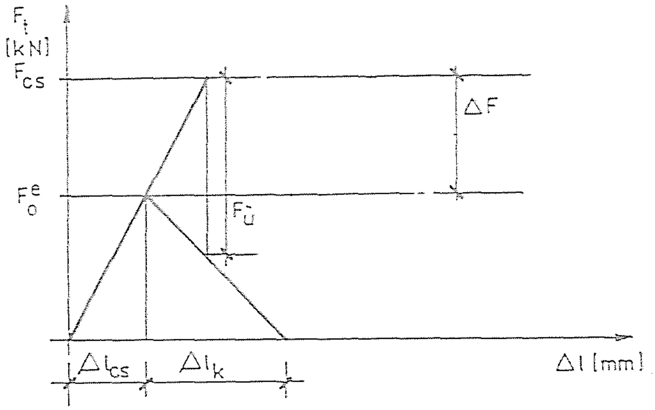

Fig. 7. Force in prestressed fastener

5.1 Analysis of Flange Plate and Tension HSFG Bolts

The calculation of flange plate and tension HSFG bolts needs the following assumptions:

- height of compressed zone – on the basis of the experimental and numerical analyses (see *Fig. 4* and *Fig. 5*) – equals the half of original beam

- cross-section of connection comprises the cross-section of compression flange(s), compression web part, flange plate and tensile area of tension bolts
- for the above mentioned cross-section the Bernoulli–Navier hypothesis is valid and the normal stresses are calculated by $\sigma = \frac{M}{J}y$ formula.

5.1.1 Analysis of Flange Plate

First, the effective area of flange plate should be taken as the tension flange of the beam, then the diameter and the number of the HSFG bolts. This way the whole cross-section is given and the normal stresses can be controlled in the extreme fibres on the basis of elementary strength theory. In the case of beam-to-column connection the beam is examined near the column anchoring tension and compression.

5.1.2 Analysis of Tension HSFG Bolt (Web Bolt)

The maximum internal load ($F_{\ddot{u},\max}$) in the connection due to external load of the beam can be calculated on the basis of the elementary strength theory by means of tensile area:

$$F_{\ddot{u},\max} = \sigma_x A_s\,,$$

where
σ_x = normal stress in the centreline of the extreme tension bolt
A_s = tensile area of the bolt

If the maximum internal load is known, the tension of bolt is calculated according to *Fig. 7* where calculation of ΔF needs the strain and spring stiffness due to prestress of the bolt and compression and spring stiffness of end-plates.

The strain due to F_0^e prestress:

$$\Delta l_{cs} = \frac{F_0^e l_0}{A_{\mathrm{mag}} E}\,,$$

where
F_0^e = prestress in bolts of end-plate
l_0 = thickness of connected ply
A_{mag} = core section of the bolt
E = Young's modulus

Spring stiffness of the bolt:

$$S_{cs} = \frac{F_0^e}{\Delta l_{cs}} .$$

The spring stiffness of ply:

$$S_k = \frac{A_k E}{\Delta l_{cs}} ,$$

where

$$A_k = \frac{\pi}{4}\left(d_k^2 - d^2\right) \qquad \text{or} \qquad A_k \approx 7 d_1 ,$$

$$d_k = s + \frac{l_0}{2} .$$

d = diameter of bolt hole
d_1 = diameter of bolt core
s = width across flats

The compression of ply due to prestressed force:

$$\Delta l_k = \frac{F_0^e}{S_k} .$$

The ΔF bolt force difference due to internal loads caused by external load of the beam is:

$$\Delta F = F_{\ddot{u},\max} \frac{S_{cs}}{S_{cs} + S_k} .$$

The maximal bolt force is:

$$F_{\max} = F_0^e + \Delta F .$$

This ΔF is neglected by ME-04-125 Hungarian standard (Application of HSFG Bolts in Building Industry) in the case of specified tension force, where the following condition should be satisfied:

$$F_{\max} \leq F_0 .$$

This condition is not in accordance with mechanical engineering practice where:

$$\sigma_{\max} = \frac{F_{\max}}{A_s} \leq \sigma_{\mathrm{eng}} = (0.8 - 0.85)\,\sigma_y ,$$

where

$\sigma_{\max}$ = maximal tensile strength
σ_{eng} = allowable tensile strength

$F_{\max}$ = maximal tensile force
F_0 = specified tensile force
A_0 = tensile area of the bolt
σ_y = yield strength of the bolt

Conclusion: totally prestressed bolt is not required by specification of ME-04-125.

5.2. *Combined Shear and Tension*

When bolts are subject to both shear and tension, the following relationship should be satisfied:

$$\sqrt{\sigma^2 + 3\tau^2} \leq \sigma_H ,$$

where

$$\sigma = \frac{F_{\max}}{A}, \quad \tau = \frac{Q}{nA},$$

where
$F_{\max}$ = maximal force of the bolt
A = nominal cross-section of the bolt shank
Q = shear force acting on the whole connection
n = number of sheared bolts
σ_H = tensile limit strength of the bolt

5.3. *Analysis of End-Plate*

By the design rules (generally by girder of low web) the thickness of the end-plate equals the diameter of bolt used in the end-plate. The yield line theory can be applied to both beam of low web and beam of high one. The latter method is necessary for beams of high web applying restrained end-plate.

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