

## Tests of the critical bolted connection of the Wendelstein 7-X coils

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## **Abstract**

The WENDELSTEIN 7-X (W7-X) superconducting coils will be subjected to high electro-magnetic forces and moments during the stellarator operation. It is therefore essential to prove that the mechanical connections which keep the coils joined together and linked to the magnet system Central Support Structure (CSS) are capable to take the operational loads during the machine lifetime.

Critical connections identified by the finite element (FE) analysis of the magnet system are the bolted Central Support Elements (CSE) between coils and CSS. The most critical one, called NPC1Z1, was studied by using mock-ups. The tests were carried out at 77K and consisted in applying the forces starting from zero and ramping them up to a given set point, so simulating the coils' energization, and back to zero. The loading steps were repeated for more than 3600 cycles in order to reproduce the W7-X lifetime, including the high load cycles, where the reference loads were exceeded with the aim to explore the limit of such bolted connection. The tests showed that the mock-ups could take the nominal loads, but at 120% of such loads plastic failure on the mock-ups occurred.

This paper presents an overview of the design and assembly of the CSE, the test mock-ups and test device, the execution of the test as well as the results and main conclusions of the experimental campaign.

**Keywords:** W7-X, stellarator, magnet system, support elements, bolted connection

## 1 Introduction

The magnet system of W7-X [1] includes 50 Non-Planar (NPC) and 20 Planar-Coils (PLC). Each coil is connected to the CSS through two CSE which transfer the forces and moments acting on the coil to the CSS itself [2].

Fig. 1 shows two coils connected to the support structure, while the typical design of a CSE is illustrated in Fig. 2.

According to the FE analyses performed on models of the magnet system [3] the CSE are subjected, during operation at 4K, to forces and moments in the order of 1500 kN and 300 kN·m respectively. In one case in particular, i.e. the connection for the Non Planar Coil type 1, named NPC1Z1, high loads and significant “opening” (~1 mm) of the interface flange between coil and CSS are expected during operation.

Therefore, a test campaign was organised on full scale mock-ups of NPC1Z1 in order to verify that the connection is able to sustain the loads for a number of cycles which is representative of the life-time of the W7-X stellarator.

## 2 Design and test activities

### 2.1 CSE and mock-ups design

The CSE design (Fig.2) includes a matrix of long studs (3x3 M30) which are tightened using special SUPERBOLT® nuts between the coil and the CSS. To be able to take the operational loads, two flanges belonging to the coil and to the CSS are highly pre-compressed by the studs. In such way shear forces and torque are reacted by friction at the flange interface and axial force and bending moments are reacted by pre-compression. The CSS flange is equipped with wedged shoulders to be able to react in

case shear forces and torque would exceed the reactive friction forces. Bolts, sleeves, nuts and washers are made of high-strength Inconel 718 and the other main components are made of AISI 316 LN.

The rationale for this design is:

- bolted, instead of welded connection, limits distortion during the assembly process and make it easier, and in general decrease the CSE reaction bending moments during operation (“flexible joints”);

- long and slender bolts better adsorb deformations, and sleeves made of the same material limit the loss of pre-load (typically to ~7%, due to differential thermal shrinkage between stainless steel and Inconel) during cooling down from RT to 4K.

To validate this design, two identical full-scale mock-ups (Fig.3) representing NPC1Z1 were prepared and subjected to two different types of tests: High Load Tests on mock-up A and Cyclic Tests on mock-up B, followed by another High Load test on the same mock-up.

Each mock-up, made of the same materials as in the real W7-X, was actually composed of a row of 3 bolted elements (Fig 3), i.e. one third of the real connection which shows a 3x3 bolts matrix which tightens together the coil and CSS extension. Out of the six forces and moments acting on the real NPC1Z1, a subset of them - the “dominating” loads - was applied, i.e. the pulling force  $F_x$  oriented like the axis of the bolts (vertical) and the transversal force  $F_z$  (horizontal), which generates also the bending moment acting in the 3-bolts axes plane (Fig.4).

Having in the mock-ups 1x3 bolts instead of 3x3, these loads were scaled down to 1/3 of the reference values.

The test device is shown in Fig.5. The mock-up is connected to the loading system (two hydraulic pistons) and to the hosting steel frame. The tests were carried out at 77K (while the real CSE will operate at 4K) by immersing the mock-up in a static bath of LN2 inside a cryostat.

During tests following data have been acquired:

- preload measured by strain gauges on bolts and sleeves,
- bending in  $0^\circ$  (z- axis) and  $90^\circ$  (y- axis) directions on bolts and sleeves measured by strain gauges,
- deformation of the threads of the support block due to preload and external loads and gapping of the flange by three gapping extensometers (Fig.6),
- vertical and horizontal displacement of the mock-up,
- temperature of the mock-up,
- bending of the support blocks measured by strain gauges,
- external loads in horizontal (z) and vertical (x) axes.

Additionally, acoustic sensors on the loading frame have been applied during the test on mock- up B.

Test campaigns were carried out by applying the  $F_x$  and  $F_z$  forces starting from zero and increasing them linearly up to a given set point, as calculated by the Finite Element model of the magnet system when the maximum magnetic field (3 Tesla) is generated.

## 2.2 Test campaign on mock-up A (High Load Test)

The objective of the high load tests was to have a first screening of the mechanical strength of the connection.

The test program of mock-up A included the following steps:

- assembly and bolts tightening up to the reference value (~500 kN on each bolt),
- installation and welding of the wedges in between the “coil block” and the CSS shoulders,
- re-tightening of the bolts up to the reference value (following the loss of pre-load during welding due to plastic relaxation in the coil block of the mock-up),
- preliminary load cycles at RT (to check the load system and to benchmark a FE model),
- cooling-down to 77K by immersion in LN2.

Execution of loading cycles at loads progressively and proportionally increased ( $F_x/F_z = \text{const}$ ) up to and above the reference nominal values ( $F_{x_{\text{nom}}} = 455 \text{ kN}$ ,  $F_{z_{\text{nom}}} = 270 \text{ kN}$ ). Load cycles were performed at 40%, 50%, 60% etc., up to 100% and more of nominal values, at 10% step increase.

The main results can be reported as follows:

- A maximum load of 546 kN vertical and 324 kN horizontal was applied to the mock-up. The test was stopped when the bending in the support block produced significant plasticity in that area (~ 0.4%), see also [1].
- Improvements were identified for the design of the SUPERBOLT® nuts (Fig.7), which were implemented by the supplier for the next test on mock-up B.
- Significant loss of preload (~25%) were observed during wedge welding due to plastic relaxation of the threads of the coil block caused by temperature increase, therefore modification to the assembly sequence were introduced

- Bending stresses in the bolts and sleeves up to 50 MPa caused by machining errors (threaded holes axes not perpendicular to the contact surface) during tightening were recorded.
- Loss of pre-load, in the order of 1.5 – 2%, after final tightening at 500kN were observed due to settling effects induced by plastic relaxation of the coil block threads (~0.07 mm).

### 2.3 Test campaign on mock-up B (Cyclic Tes & High Load Test)

The objective of the cyclic tests was to verify that the bolted connection was able to take the given loads for a number of cycles which is representative of the life-time of W7-X. A summary presentation of test sequence with mock-up B is given on Fig.8.

The load nominal values applied in the test were increased with respect to those used for mock-up A, according the new results from the updated FE model of the magnet system.

In mock-up B the wedge welding was carried out at reduced preload (~ 170 kN), the loss of preload was ~ 30 kN this time. Then the SUPERBOLT® nuts were tightened up to ~ 500 kN and similar settling effects as in mock-up A were observed.

Following verification tests at RT and at 77 K, to check that the response of mock-up B was similar to that of mock-up A, the test campaign consisted of three main sequences:

- Preliminary runs at 50%, 60% and 70% of the nominal load level, 10 cycles at each level,

- 3200 cycles at 80% of the nominal load level:  $F_z = 270 \text{ kN}$ ,  $F_x = 464 \text{ kN}$

(corresponding to  $B=2.5T$ ),

- 400 cycles at 100% of nominal load level:  $F_z=330 \text{ kN}$ ,  $F_x=575 \text{ kN}$  (corresponding to  $B=3T$ ). Before that, 10 cycles at 90% load level were performed.

After completion of the cyclic test campaign the High Load Test was carried out on mock-up B by increasing the loads in a stepwise approach.

The loads  $F_z$  and  $F_x$  were applied to the mock-ups in synchronised way. The ramp-up and ramp-down velocity was  $\sim 17.2 \text{ kN/s}$ ; with a 5 s dwell time at the set point.

The main results of test campaign with mock-up B can be reported as follows:

- The maximum load combination achieved during High Load Test was 507 kN ( $F_z$ )/ 684 kN ( $F_x$ ), where significant plasticity ( $\sim 0.3 \%$ ) on the most loaded bolts was observed and the test was therefore stopped.
- During the test cycles at 80% load level no plastic effects were detected. The interface flange started to open at this load level, but the load cycles could be completed without problems.
- Opening of the interface flange of 0.83mm at 80% load level and 1.68mm at 100% load level were detected (Fig. 9)
- The first plastic effects on the most elongated bolt were detected at the load level 360/575 kN ( $\sim 3T$ ) - Fig.10, 11.

During the runs at 80% load level and after  $\sim 1000$  cycles sound signal started to originate, which repeated periodically in particular at 100% load level. An acoustic sensor and a 3-axis 5g accelerometer were installed to record this effect. It could be



argued that this was due to stick-slip of the wedges between the coil block and the CSS shoulder during flange opening-closure (Fig. 12 and 13).

One possible reason for stick-slip could be the wedge welding, which produces some opening of the wedge bottom due to weld shrinkage (Fig. 14).

### 3 Summary of main results

The plastic failure of mock-up A (on the coil support block) was different from that of mock-up B (on the most elongated bolt) and occurred at lower load level. It could be argued that this was due to excessive strain during pre-tests at RT, when mock-up A was overloaded; therefore the results from mock-up B are more representative.

Mock-up B showed that the bolted connection could take the cyclic loads at representative level of operational loads expected during W7-X lifetime (and for planned number of cycles) and that the safety margin to failure is about 20%. It must be also considered that some extra margin (~10-15%) should be provided by the increased material strength between 77K (test temperature) and 4K (actual operating temperature). The field of stress calculated by means of a specific FE model of the 3-bolts mock-up [5] was found substantially in line with the stress which could be detected via the strain gauges installed on the mock-up and the opening of the coil-CSS interface flange under nominal load was in the same order (~1mm) of the FE calculations. This represents a good validation of the FE simulations activities on the CSE [3].

Stick-slip effects observed during the test with mock-up B must be further investigated.

The design of the jack bolts of the SUPERBOLT® nuts was modified after the test on mock-up B showed severe plastic effects on one of them.

Significant experience has been gained also with regard to the assembly of all CSE components, which will be used for the real assembly of the W7-X magnet structure.

#### 4 Complementary activities to the 3-bolts test programme.

An FE model of the 3-bolts mock-up [5] was prepared and calibrated with the tests and is now used to benchmark other FE models of the real CSE's.

Other laboratory single-bolt tests [4] were performed to verify specific design features (e.g. spherical washers to accommodate sleeve-stud manufacturing and assembly errors).

Destructive and non destructive examinations were performed by IPP (Max-Planck Institut für Plasmaphysik, Greifswald) on both mock-ups before and after the tests (including tensile tests on material specimens) to get detailed information on how the various parts were mechanically affected by the load cycles.

#### 5 Conclusions

The complexity of the W7-X magnet system mechanical scheme requires a design-integrated approach with FE analyses, mechanical tests and assembly studies as it has been done for the CSE.

The tests performed on NPC1Z1 mock-ups have shown that the bolted connection was able to sustain the highest cyclic loads expected during the W7-X lifetime, but undesirable effects, like stick-slip on the sliding surfaces of the connection, have been observed.

A next test campaign on another mock-up (C) is now under preparation with the objectives:

- to verify the solutions to avoid stick-slip (e.g. antifriction coating on the sliding surfaces, changes in the design and wedge welding sequence),
- to check final assembly sequence with new SUPERBOLT® nuts,
- to repeat the cyclic test and high load test in order to confirm the results obtained with mock-up B,
- to finally validate the CSE design concept.

## 6 References

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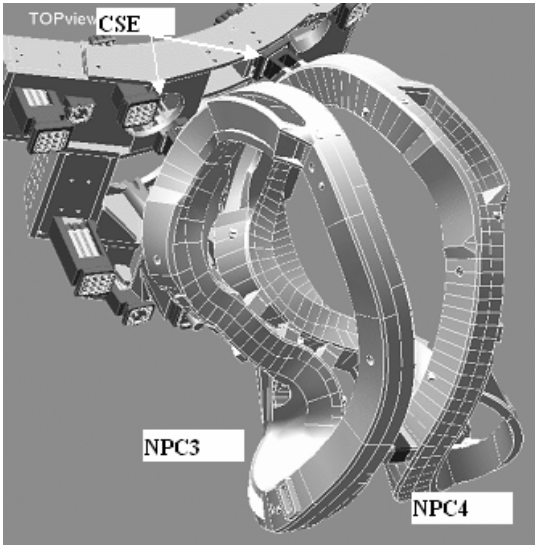


Fig.1. NPC type 3 and 4 connected between them and to the CSS.

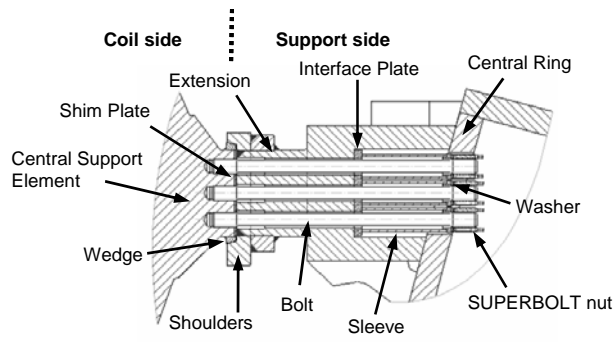


Fig.2. Cross section of a CSE

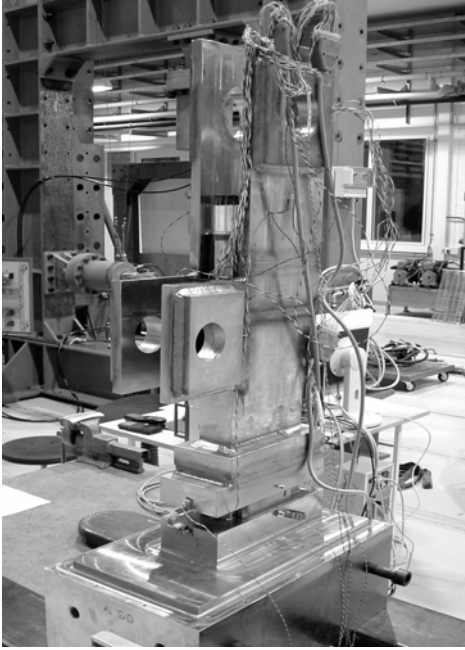


Fig.3. 3 bolt mock-up with instrumentation on board

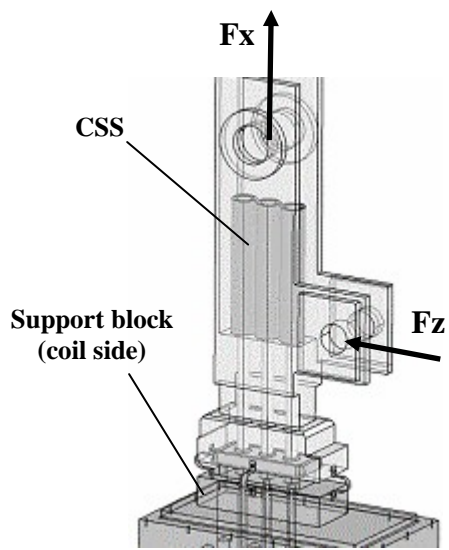


Fig.4. Scheme of forces applied to the mock-ups

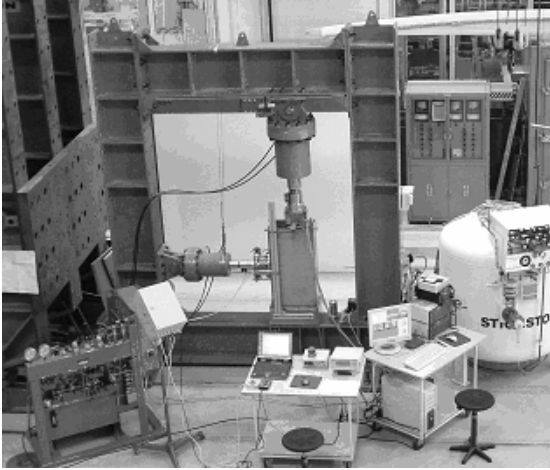


Fig.5. Overview test device



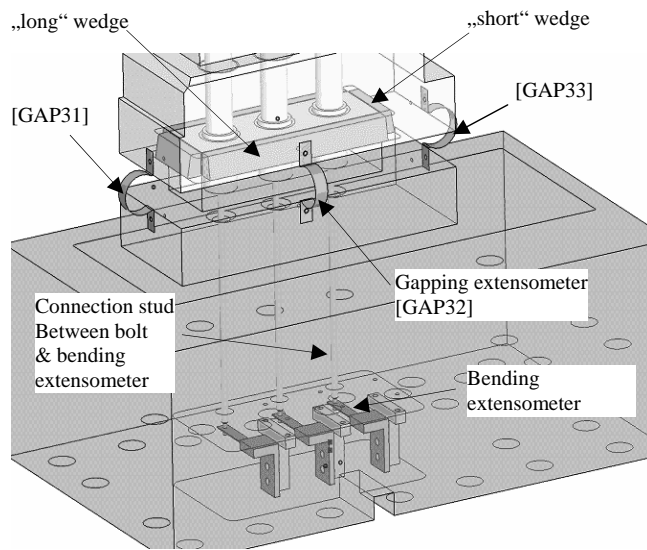


Fig.6 Bending and gapping extensometers on mock-up

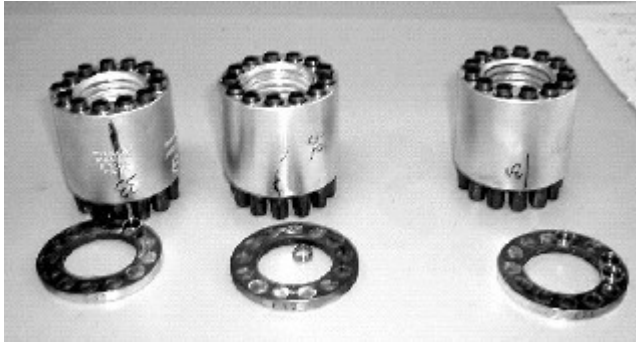


Fig.7. SUPERBOLT © nuts and washers after mock-up disassembly

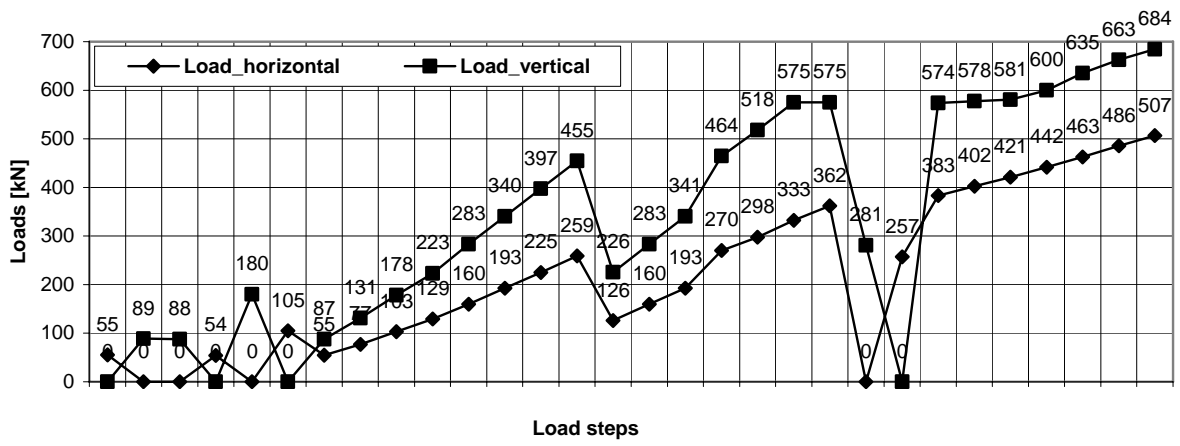


Fig. 8. Overview of test program with mock-up B (cyclic&high load tests)

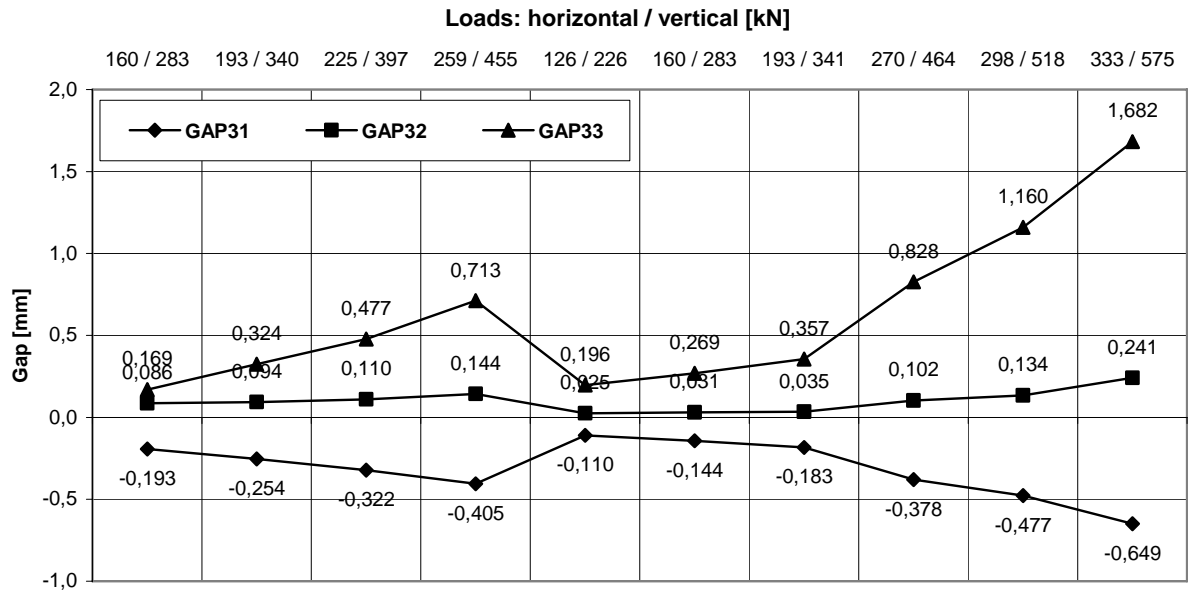


Fig.9. Gap opening between flange and support block during cyclic test (GAP31,GAP32,GAP33 – values given by gapping extensometers acc. fig.6)

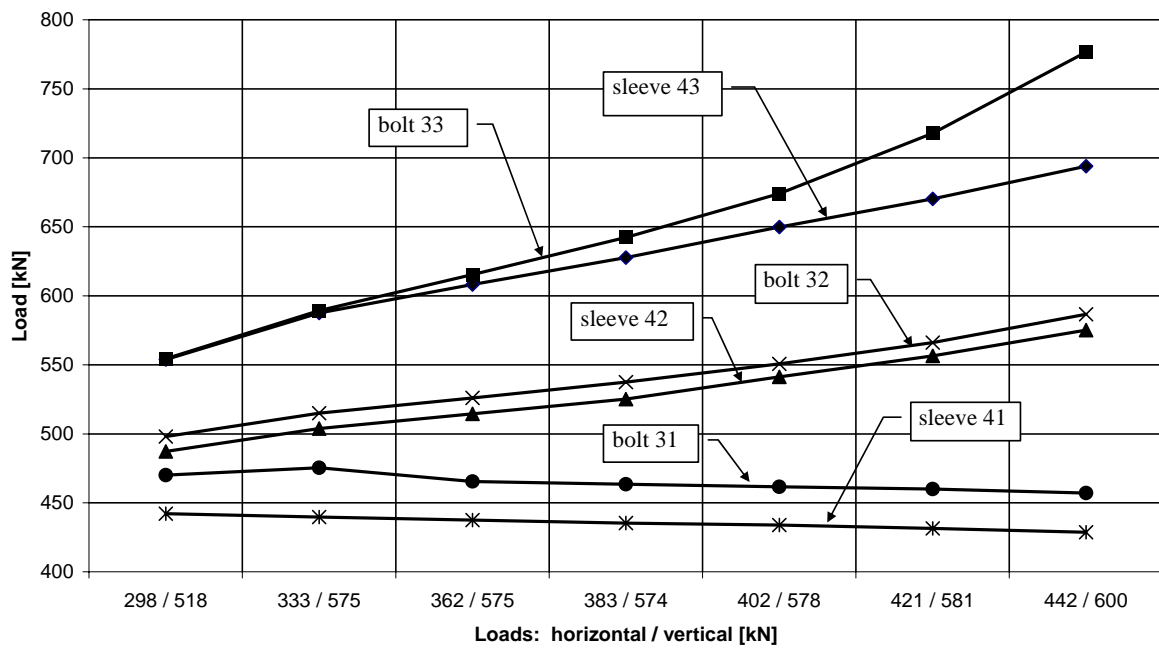


Fig.10. Comparison between detected loads on bolts and sleeves ( most loaded: bolt 33 & sleeve 43, less loaded: bolt 31 & sleeve 41)

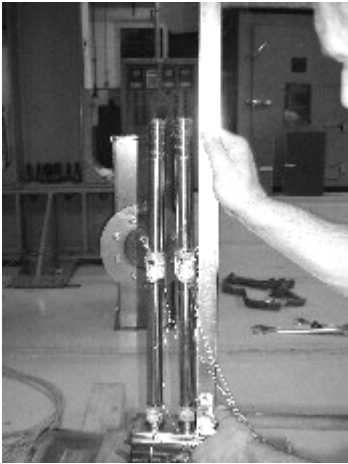


Fig.11. Deformed bolts after mock-up disassembly

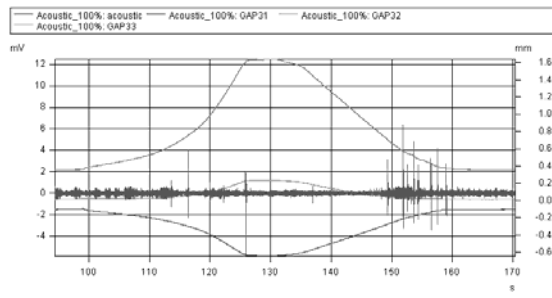


Fig.12. Example of acoustic sensor signal during a load cycle

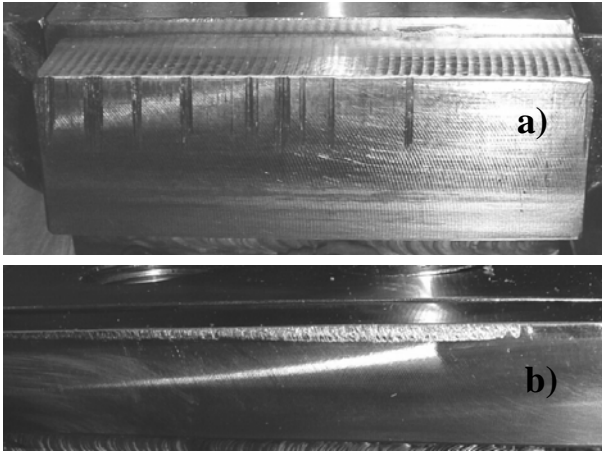


Fig.13. Wedges after mock-up disassembly: marks on most loaded “short” wedge (a); damaged edge of “long” wedges (b) ( “short”&” long” wedges” marked on Fig.6)



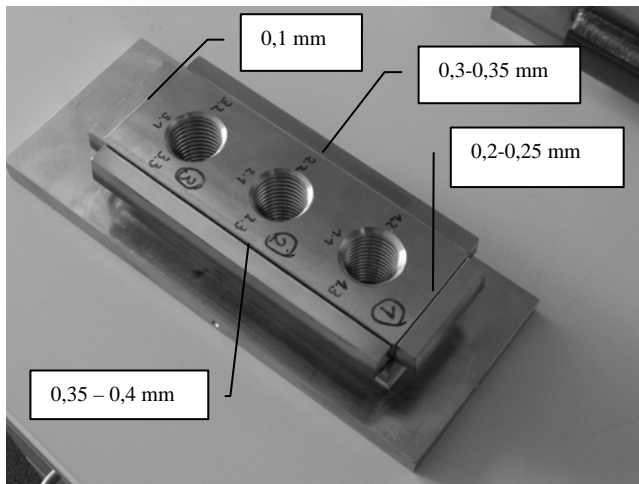


Fig.14. Support block after disassembly. Gaps between wedges and threaded block