BEHAVIOUR OF THE FRICTION LAYER IN JOINTS BOLTED WITH HIGH-STRENGTH BOLTS

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Design of friction joints is based on slip loads. Several tests have been made on the influencing factors, but test results exhibit incertainties or even contradictions. There is no unanimity even in the interpretation of tests on such a fundamental characteristic as the friction coefficient.

It will be attempted here to find a reliable interpretation for the nature of friction and its role in structural joints, making use of rather informative test results.

Rough surfaces and friction layer

The surface of engineering steel structures is always rough, faying surfaces of high-strength bolt joints used to be deliberately roughened to possibly increase the friction coefficient. Surface roughness may be of a pattern such as that of a file or of the jaw of a testing machine. This is not the case of engineering steel structure surfaces where roughness is due to purposefully made but disordered pits of finite diameter. Disorder prevents rough surface characteristics from being described by physical characteristics and by a model of ordered geometry, without specially designed tests.

It has to be assumed that only part of the two compressed, disorderly rough surfaces transmit clamping forces, and a part is able to transmit in-plane shear force. Technically speaking, transfer of compression by an entire surface cannot be imagined if not between perfectly plane and smooth (hence other than rough) surfaces or in case of extremely high compressions; neither being the case of rough engineering surfaces.

Imperfectly fitting pits and crests of rough surfaces transmitting the force are no doubt a less rigid entity than is the solid outside the roughness range. From the aspect of force transfer, it seems thus justified to assume a friction layer with properties different from those of the basic material, e.g. lower rigidity.

Knowledge of the assumed friction layer properties, primarily the relation between the shear force parallel to the surface and the parallel displacement of the friction layer, detected experimentally, would permit to range the friction joint among shear joints determined theoretically and experimentally, and to extend relevant design theories (e.g. [1]) over them.

Theory of the behaviour of shear joints requires the knowledge of the force-displacement relationship for the load transfer member of the joint, rather difficult to determine experimentally. In case of a continuous joint layer (e.g. adhesive layer), experimental determination of the behaviour of an infinitesimal length would be needed. This is practically unfeasible, a finite length of a layer, exhibiting constant deformation and force distribution, has to be made up with instead.

Tests are made usually on double-shear overlapping joints. Displacement is, though with uncertainties, but directly accessible to measurement. Friction joints have been found to be stiffer than adhesive layers (or even than fasteners), so that specimens of a high sensitivity to the displacement of the friction layer have to be designed even if the displacement is manifest indirectly, by its consequences.

Such a specimen would be a prismatic main plate in tension with bilateral stiffening plates.

Forces and deformations in specimens with stiffening plates

Figure 1a is the scheme of a specimen with stiffening plates. The two stiffening plates of identical cross section, arranged according to Fig. 1, are only loaded through fasteners spaced at $2l$.

Equilibrium equation of the interval of $2l$:

$$P_1 + P_2 = P;$$

the deformation equation (Fig. 1b):

$$e = l_2 - l_1,$$

or, in terms of specific strain:

$$e = l(\varepsilon_2 - \varepsilon_1).$$

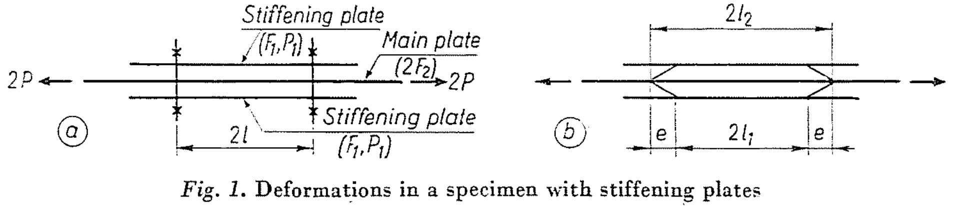

Fig. 1. Deformations in a specimen with stiffening plates

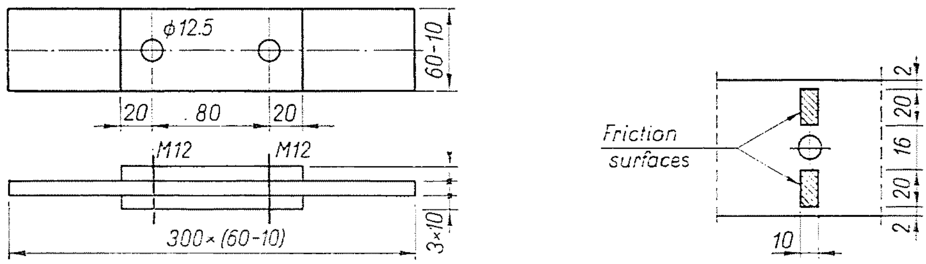

Fig. 2. Specimen with stiffening plate

For each load increment, ε_2 and ε_1, P_2 and P_1, as well as fastener deformation can be calculated from plate strain values. For testing the friction layer, the fastener is represented by friction spots spaced at $2l$, purposefully designed, and assumed to act concentrated (Fig. 2).

In case of a friction layer of similar arrangement but acting all over the faying surface, the force-displacement diagram of the friction layer can be determined by using (1) to the sense, but the calculation is much more tedious than for a friction spot, and the result is made rather uncertain by error accumulation. The solution for linear force-displacement diagrams is known since ARNOVLEVIC [3].

Tests on tensile specimens

Specimens have been made of high-strength steel 60 by 10 mm nominal size, as seen in Fig. 2.

Friction spots 2 cm^2 in area spaced at $2l$ were symmetric about the boring axis bilaterally of the main plate, the surface of which was ground to a total thickness of 0.1 mm outside the friction spots to prevent force transfer. Friction spots were roughened by means of 1 mm carborundum grits. Strains were measured at borehole mid-spaces along plate edges, using 5 mm Kyowa strain gauges. Three identical specimens have been made in all, but these were re-used. The prestress was achieved by tightening Peine bolts type M 12 grade 10.9 by torques of 3.5; 5.25; 6.0; 8.0; 8.5; 10.5 kpm.

Specimens were loaded in a 10 Mp tensile testing machine up to a load limit of 9500 kp. Load increments were 250 to 1000 kp, but only measured data for round 1000 kp load increments were evaluated. The load can be considered as static, load was applied on each specimen gradually during 1.0 to 1.5 hours.

Evaluation of test results

Plots of the force-displacement diagram of the friction layer, calculated from test data, are seen in Fig. 3. Up to the limit load of 9500 kp, some specimens achieved, others not, load capacities of the friction layer, i.e. the maximum force transferable by friction. The friction (shear) coefficient calculated from the friction layer load capacity ranged from 0.52 to 0.54. Phenomena preceding the load capacity drop — conventionally called slip — let conclude on similar friction coefficients for specimens exempt of "slip" up to 9500 kp.

Conclusions drawn from force-displacement diagrams:

1. Force-displacement diagrams are by far not linear.
2. Friction layer rigidity is function of the force acting on the layer.
3. Since in the present test, surface roughness, friction coefficient and friction spot areas may be considered as about equal, displacement diagram depends on the prestressing force (on the belt torque). From the aspect of friction layer behaviour, it is advantageous that in the tested range, the higher prestress adds to the displacement diagram area (cf. [1], [2]).
4. The displacement until load capacity drop (slip) is rather slight (0.015 to 0.020 mm), much less than for an adhesive layer (about 0.1 to 0.2 mm up to failure), or of the fastener (of the mm order up to failure). Hence, from the aspect of interaction between friction layer and high-strength bolt or

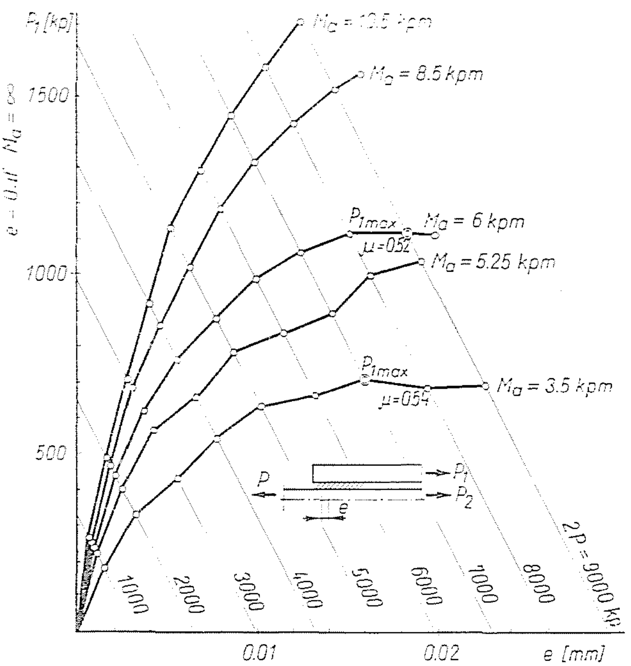

Fig. 3. Force-displacement diagram of the friction layer

other fastener, in general, the post-slip section of the displacement diagram has to be reckoned with.

5. After unloading the specimen, important tensile force remains in its directly loaded main plate and in the stiffening plates important compressive force balancing this tension subsist. After several loading cycles, values of these permanent internal forces did not change, hence, after subsequent loading, the stress in the stiffening plate (sum of the permanent compressive and load-induced tensile forces) varied by more, and that in the directly loaded tensile main plate by less, than in the first loading cycle.

6. Under different prestresses, plots of the force-displacement diagrams corresponding to load increments of 1000, 2000, ... are seen to lie on skew straight lines each. On the displacement co-ordinate axis in Fig. 3, skew line intersections are strains of the main plate corresponding to prestress $M_a = 0$ for the given load increment. In the case considered, for an outside load of 1000 kp, $e = 0.0033$ mm. Along the force axis, $e = 0$; intersections express the force value in the stiffening plate, corresponding to the rigid connection ($e = 0$, $M_a = \infty$) between the three united plates. In the given case, this amounts to 335 kp for an outside load of 1000 kp.

In case of full-area load transfer, the force-displacement diagram of the friction layer can be used for load capacity calculation of the friction layer, or for designing the friction layer to the sense [1], assuming a uniform surface compressive force. Behaviour of tightened bolt joints seems, however, to be better described by assuming friction spots.

Post-slip behaviour of the friction layer

The stiffening-plate specimen facilitates determination of the load-displacement diagram of the friction layer up to an outside force of 9500 kp in our case, else up to the proportionality limit of the specimen. In case of adequately selected proportions, deformations preceding and directly following the slip are clearly perceivable. Much greater displacements do not suit this specimen but require one permitting greater displacements. Practically, also greater displacements are of importance, since the interaction between high-strength bolts and friction layer belongs, at least partly, to the post-slip range, even if tightened bolts have been applied.

To test greater displacements, a flexural beam has been designed, where the mid-cross-section moment has been transmitted by an annular friction layer, deformation of which can be calculated from the rotation at mid-cross-section. Because of metrology difficulties, rotation was not directly measured but calculated from vertical displacements in the beam cross sections 4 to 9. Since the vertical displacement is a combination of those due to bending and to mid-cross-section rotation, these two effects are difficult to distinguish. Along the beam length, the displacement from rotation varies linearily, and that from bending parabolically.

Test results yield the following conclusions:

1. The flexural specimen is not reliable enough for vertical displacements under slight loads. Besides, friction layer rigidity values were of the order of those for tensile specimens.

2. Post-slip displacement of the friction layer is accompanied by load capacities concomitant to friction coefficients growing low.

3. The surface of one specimen was sprayed with aluminium. It had a friction coefficient much above that of the uncoated one. Also the post-slip force-displacement diagram was much superior, in spite of the visibly higher liability to creep. This is in agreement with our ideas on the friction layer, exhibiting properties hinting to a very slight thickness. Aluminium coating permits a greater part of compressed surfaces to share force transfer under the same prestress, at the same time, the aluminium coat, softer than steel, adds to the friction layer thickness. Both improve friction layer properties.

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Summary

Design of friction-type joints is based on the slip load, but tests for determining the friction coefficient are rather uncertain to evaluate.

A friction layer able to deformation and to force transfer has been assumed — as jointing layer. Test results for deformation properties of the friction layer have been presented.

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