INFLUENCE OF THE PRYING EFFECT ON THE FATIGUE RESISTANCE OF THE BOLTS

Eugène Piraprez
CRIF - Steel Structures Department

Jean-Pierre Jaspart
University - MSM Department

Liège, Belgium

Abstract

The fatigue resistance given in the codes for bolts dynamically loaded in tension is very low (class 36). Nevertheless, tests have shown that this value can be unsafe if the influence of the prying effect is not considered to evaluate the force acting on the bolt. On the other hand, when there is no prying effect in the connection, the design fatigue resistance of a bolt can be increased from class 36 to class 100.

Taking into account the influence of the prying effect is absolutely necessary; it can avoid a dangerous situation or in other configurations of connections, it can strongly reduce the number of required bolts (till 65 %).

1 INTRODUCTION

In many different bolted connections, the fasteners are loaded in direct tension. In such cases, the relative stiffness of the bolt assembly and of the connected parts affects the connection behaviour.

In a simple bolt assembly, axially loaded, where the bolt is preloaded, the external load will produce little change in the internal bolt load until the applied load approaches the initial tension or preload in the bolt. If repeated external loadings are applied to a structural bolt but do not change the internal bolt load significantly, the bolt will not fail as a result of the loading. This was shown by tests on simple bolts in tension conducted a long time ago, in several laboratories, etc. [1] to [8].

When bolts are assembled in a pattern to resist a tensile loading, deformations of the connected elements may subject the bolts to a prying action as well as to a direct force. The effect of the prying action is to increase the total load that must be resisted by the bolts. However, if the bolt preload exceeds the force resulting from the external load plus the force due to the prying action, there will be no appreciable change in bolt load on the application of the external force and again, the bolts will not fail under the repeated loadings.

A very important research work has been done, mainly at the Technical University of Delft [6], [7], [12], ... to show the influence of the preload of the bolt and of the position of the contact point between the plates (see figures 1 and 2), on the fatigue resistance. In other words, to show the influence of the prying effect. In these figures, F_p represents the bolt preload, F_c the clamping force and ΔF_b the variation of the axial force in the bolt; F is a generic symbol for forces. But at that moment, the concept of the prying action was not well known and it was impossible to quantify it by calculation.

It is very evident that the prying effect has a large influence on the fatigue resistance of a bolt. The tests performed in Delft on specific connections, as those shown in fig. 1 and 2, have clearly shown this problem. They also have the advantage to give general rules to design a connection keeping in mind the fatigue resistance. These tests have been very useful to change the "philosophy" of the engineers for what regards the conceptual design of the connections.

However, on actual connections, where these proposed solutions are not possible, only results of tests proving the influence of the preload in the bolt on its fatigue resistance are available, but very few information exist on how to evaluate the prying effect.

An important research aimed at (1) performing new tests on connections, (2) establishing formulae to evaluate the prying effect and (3) deriving new fatigue design curves for bolts, is presently in progress in Liège.

2 POSITION OF THE PROBLEM

Until now, no international official document gives values of the prying effect in real connections; it is only written that this effect must be taken into account for the design of the connection. But it is not explained how to evaluate it.

In some national codes, the value of the prying effect is estimated, e.g. 20 % of the external axial load, but no other explanation is given.

To take a constant value for this effect can sometimes be overconservative, but can also be very unsafe in some cases.

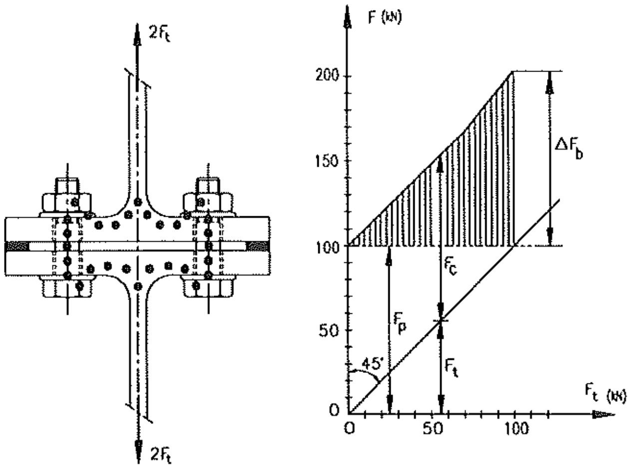


Fig. 1 - Contacts at the edges of the connection : large solicitation of the bolts.

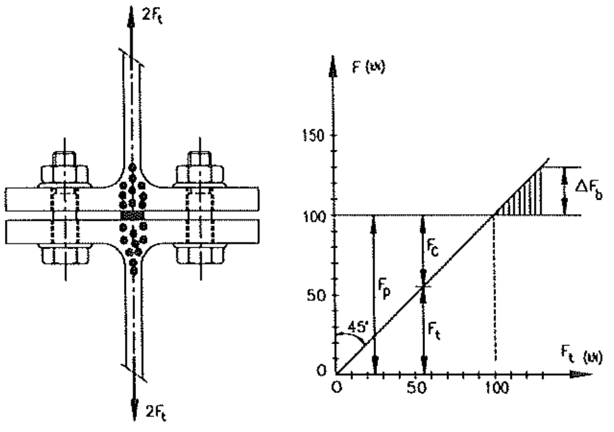


Fig. 2 - Contact at the centre of the connection : small solicitation of the bolts.

The rules given in this respect in Eurocode 3 [11] are extremely severe; in chapter 6 concerning the design of the connections, it is stated that the prying effect must be evaluated and, when fatigue loading occurs, it is necessary to refer to the fatigue resistance curve given in chapter 9. It has to be known that :

- this Wöhler curve [fig. 3] has been calibrated on tests results carried out on specimens where prying effects sometimes occur and sometimes not;
- the presence or not of prying effects has not been taken into consideration when evaluating the variation of stresses $\Delta\sigma$ in the bolts;
- $\Delta\sigma$ is based on the evaluation of a so-called normal axial load in the bolt - obtained by simply dividing the total force on the connection by the number of bolts in tension - and not on the actual one.

Taking into account two times the effect of the prying action gives completely unrealistic results.

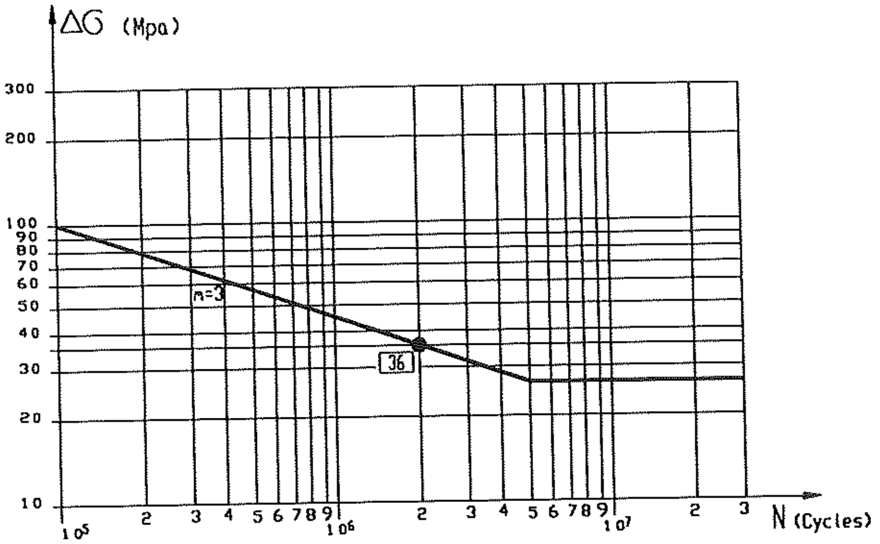


Fig. 3 - Fatigue strength curves for bolts in tension according to Eurocode 3.

3 GOAL OF THE RESEARCH

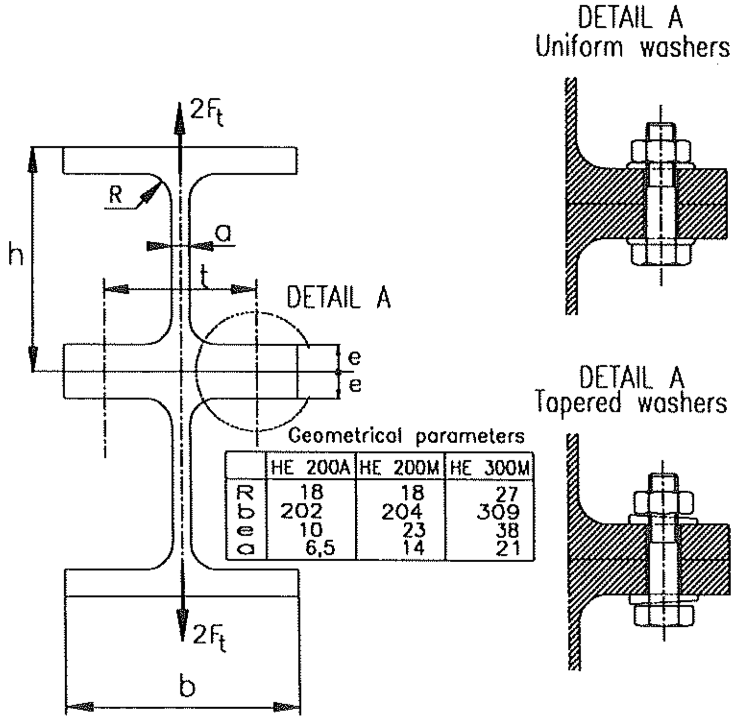
Because the fatigue life of a bolt in tension is depending on the actual force transmitted to the bolt and not simply on the nominal applied load defined here above, the effect of prying action, if it exists, must be determined so that the actual load in the bolt may be known.

At this moment, this effect has never been evaluated; only its influence has been demonstrated by means of a lot of tests on specimens in which the value of several parameters influencing the prying action were varying. These tests, as well as new ones recently performed (see below), will be used now to calibrate formulae aimed at evaluating the increase of load in bolts, due to this action, without carrying out tests.

4 TESTING DEVICE

Bolts connecting two flanges of I beams were submitted to dynamic tension loading, as indicated on fig. 4.
The frequency of the solicitation was 10 Hz.

In most of the cases, a gap remains between the connected flanges in the centre of the connection; even after preloading the bolts.



	HE 200A	HE 200M	HE 300M
R	18	18	27
b	202	204	309
e	10	23	38
a	6,5	14	21

Fig. 4 - Specimen of tested connection.

5 TEST PROGRAMME

Numerous parameters were taken into account. The geometrical parameters of the connected parts are given in fig. 4. Moreover several parameters concerning the bolts were considered :

- the diameter : 16, 20 and 27 mm;
- the grade : 8.8 and 10.9;
- the manufacturer : German and Italian;
- the type of washers (see fig. 4) : uniform or tapered (8 %);
- the bolt prestress : 0.2 and 0.8 f_y.

Obviously, different stress ranges $(\Delta\sigma)$ were adopted for each combination of these parameters, but in all cases, the maximal nominal load in the bolt amounts $0.6\ f_y\ A_s$.

6 EVALUATION OF THE STRESSES IN THE BOLTS

Three types of stress ranges were considered for the interpretation of the results :

- the theoretical value $(\Delta\sigma_{th})$ calculated without taking into account any prying effect; so it is equal to $\Delta F_t/A_s$ when the bolt is not preloaded and equal to 20 % of this value when the bolt is preloaded. This value of 20 % is about equal to the ratio of the rigidities of the bolt and of the connected parts in the most usual connections; it is adopted in several codes.

  ΔF_t is the external load range per bolt

  A_s is the stress area of the bolt

- the mean actual value in the stress area $(\Delta\sigma_{mean})$ given by the variation of deformation recorded by means of an axial strain gauge in the non-threaded part of the screw and multiplied by the ratio $(E * A_{nom}/A_s)$, where A_{nom} is the nominal section of the bolt.

- the maximal value $(\Delta\sigma_{max})$, calculated in the stress area, considering a trapezoidal stress diagram in place of a rectangular diagram. This difference is due to the bending of the bolt, as shown on fig. 5. For the calculation, it is assumed that the curvature is constant and that it occurs only in the threaded part of the screw (ℓ_{th}), under the nut. The rotation of the end of the screw (α on fig. 5) was measured and, in accordance with the previous assumptions, the stress range to add to the mean stress range is given by the following expression :

$$E d_s \alpha / 2 \ell_{th}$$

where d_s is the diameter of the stress area.

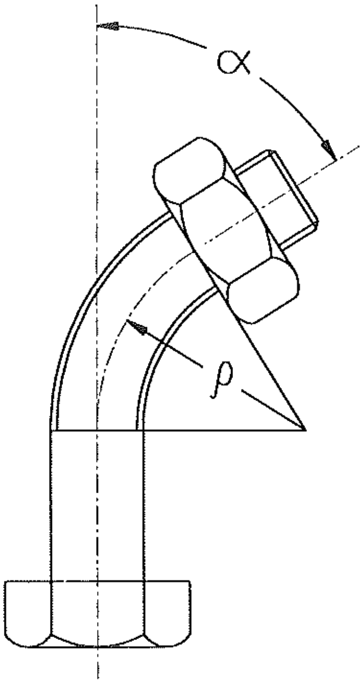


Fig. 5 - Hypotheses about the bending of the bolt.

The deformation of the strain gauge and the rotation of the end of the screw were measured during tests under static loading performed on each configuration of connection. A complete report with all detailed results will be published very soon.

Regarding to the results of the static tests, very important general comments can already be given :

- when the bolts are non-preloaded, the mean stress is little influenced by the configuration of the connection; the bending of the flanges is not very important and the increase of the stress is about 10 %. This result is due to the relatively high ratio between the stiffness of the plate in bending and that of the bolt in tension.

- when the bolts are preloaded, the induced axial stress range can be 4 times larger than the theoretical one; so, it can be equal to 80 % of the stress range of a non-preloaded bolt, and not to 20 % as it is generally assumed. This stress increase is not due to the bending of the flanges, but to the influence of the position of the contact points between these flanges. This remark is fully in line with the conclusion of previous researches [6], [7], [12];
- the taper of the washer has no influence;
- in all cases, the maximal stress range is about equal to 2 times the mean stress range :

$$\Delta\sigma_{max} \cong 2\,\Delta\sigma_{mean}$$

7 RESULTS OF TESTS UNDER DYNAMIC LOADING

As mentioned before, fatigue tests were carried out with several load ranges, but in all the cases, the maximal nominal load was equal to $0.6\ f_y\ A_s$.

The results of these tests are reported on the diagram

- of the figure 6 in relation with $\Delta\sigma_{th}$
- of the figure 7 in relation with $\Delta\sigma_{mean}$
- of the figure 8 in relation with $\Delta\sigma_{max}$

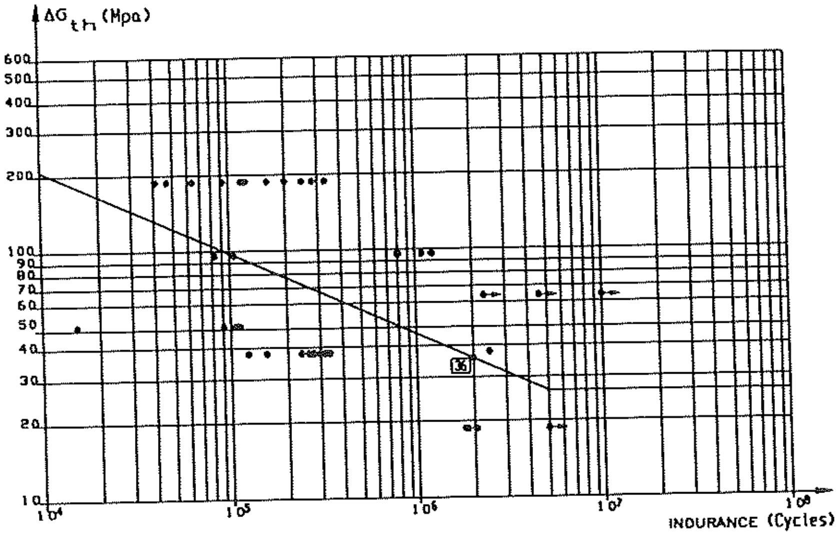


Fig. 6 - Results of fatigue tests in relation with $\Delta\sigma_{th}$.

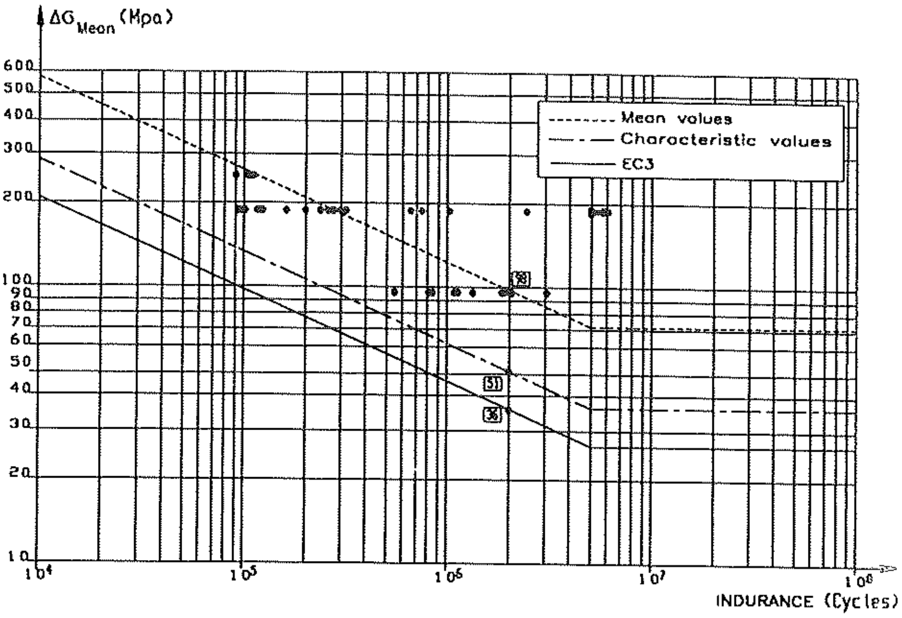


Fig. 7 - Results of fatigue tests in relation with $\Delta\sigma_{mean}$.

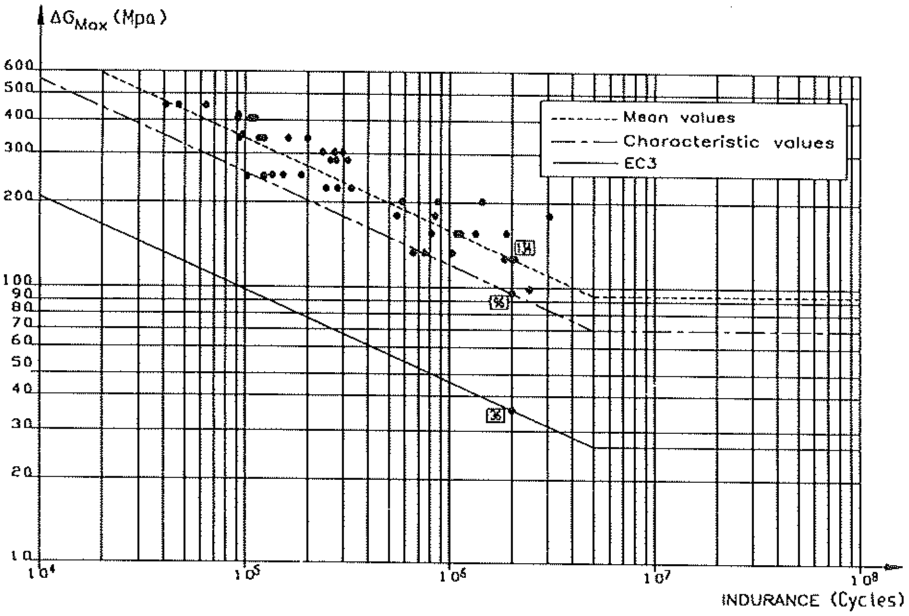


Fig. 8 - Results of fatigue tests in relation with $\Delta\sigma_{max}$.

These results confirm the conclusions of the static tests. The characteristic values given in figures 7 and 8 are very conservative due to the small number of results, but it is clear that :

- do not consider the prying effect can be dangerous, even with reference to the fatigue resistance given in the European pre-norm [11];
- to refer to this fatigue resistance is very safe if there is no prying effect; in this case, the class of resistance is about 100 MPa in place of 36 MPa;
- if we only consider the mean stress in the bolt, taking into account the prying effect, the fatigue resistance is at least 51 MPa, but the mean value is 98 MPa and with a larger number of results, the characteristic value could be about 70 MPa;
- if we consider the actual maximal stress value in the bolt, the characteristic value of the fatigue resistance is about 100 MPa, which is the resistance of an axial loaded bolt.

8 THEORETICAL EVALUATION OF THE PRYING EFFECT

Instead of using strain gauges to evaluate the influence of the prying effect, it is possible to calculate it by means of formulae recently developed [15] to characterize the stiffness of the so-called semi-rigid connections.

These formulae allow to predict the axial force in the bolts; they take the out-of-flatness of the flanges of the I-profiles (fabrication tolerances) into account, as well as the actual level of preload in the bolts. Their background will be given in the above mentioned forthcoming report.

For all the tests described in section 5, the stress range in the bolts has been evaluated through these formulae $(\Delta\sigma_{calc})$ and a good agreement was found with the measured values $(\Delta\sigma_{mean})$. The corresponding fatigue resistances are 85 MPa for the mean value and 42 MPa for the characteristic one. They have to be compared with the values 98 and 51 (fig. 7) based as the measured values $\Delta\sigma_{mean}$.

9 GENERAL CONCLUSIONS

The very low fatigue resistance given in the codes for bolts submitted to tension loading can be on the unsafe side if the influence of the existing prying effect is not considered. On the other hand, if there is no prying effect, the values of the codes are too much conservative.

The prying effect is much more influenced by the position of the contact points between the connected plates than by the stiffness of these plates.

When the real mean stress in the bolt is determined, either by strain gauges during tests or by calculation, the fatigue resistance is in a class higher than 50 and probably in a class closed to the 71 one, in lieu of the class 36.

Moreover, if the real maximal stress is evaluated, the resistance is at least in the class 100, which corresponds to the resistance of an axial loaded bolt.

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