STRESS INTENSITY FACTOR SOLUTIONS FOR A CRACKED BOLT

G. G. Reibaldi

Mechanical Systems Division, European Space Agency/ESTEC, Postbus 299, 2200 AG Noordwijk, The Netherlands

ABSTRACT

Bolted joints are very common in aerospace structural components, nevertheless, their behaviour is not yet fully understood, especially if a crack is present when defect tolerance is requested. Stress intensity factor solutions (mode I) of a cracked iso-metric bolt derived from a three dimensional F.E. model are presented.

In the F.E. model the crack shape has been modelled with special isoparametric singular elements. Four different crack lengths (depths) have been considered in the analysis starting from 0.5 mm up to 1,2,3, mm.

Three different loading conditions have been assumed in order to assess the influence on the stress intensity factor solutions of the pressure load acting on the bolt thread.

Comparison with existing data has been carried out.

KEYWORDS

Bolt, thread, stress intensity solution, finite element, load, mathematical model, test, semi-circular flaw.

INTRODUCTION

Bolted joints are classical components of any type of aerospace structure. Nevertheless, their behaviour and analysis is still not well understood. There are many sources of uncertainties in analysing the bolted joints ranging from the coefficient of friction to the interface force and stress distribution, flexibility of the joints and so on.

The problem is more complex if a crack is present in the bolt. In the aerospace industry the damage tolerance concept is widely applied for safety reasons. In particular for the safe life approach it is important to demonstrate that the operational life is reached by a component without failure.

A three-dimensional finite element model of a cracked isometric M14 bolt was developed. Possible extension of the results to other types of threads have been also indicated.

DESCRIPTION OF THE PROBLEM

An M14 bolt was analysed. The problem of a cracked bolt is very difficult and it cannot be treated by analytical methods to derive stress intensity factor solutions. The only solutions available in the literature were 2D stress intensity factor solutions for an edge crack in a bar. The geometrical effect of the thread was considered by a correction function, but the load effect on the thread was ignored. Because of the elicoidal thread shape in space, the stress field generated by a bolt is fully three-dimensional.

In order to simulate as much as possible the reality of a cracked bolt a three dimensional finite element analysis was performed to evaluate the pattern of the stress intensity factor functions on the crack front.

Four different crack fronts were considered for the present analysis with crack depths of 0.5, 1, 2, 3 mm respectively. For each crack depth a constant a/2c = 0.5 was assumed. The reason for having these four crack depths was to study the variation of the stress intensity factor with respect to the thread dimensions.

LOAD CONDITIONS

Experience shows that about 65% of bolted joint failures occur at the first thread turn in contact between bolt and nut, ref. [5].

Many investigators tried to explain this phenomenon by calculating the load distribution between thread turn and proving that the first turn in contact is supposed to carry much more load than successive turns.

It is believed, refs. [7] and [8], that the first turn completely in contact is subject to about 30 - 35% of the total bolt load, that is thread A, see Fig. 1. In fact the failure due to fatigue is a surface effect. Furthermore, ref [4], the pressure distribution on the threads is not influenced very much by the coefficient of friction, but if there is an influence, it is towards the load distribution along the thread.

Because of the above, and mainly because of the uncertainties of the actual load acting on the threads, three different loading conditions were considered.

a) Load Case I

An axial load is distributed as 35% of the load considered uniformly applied on one side of the bolt (section A-A, Fig. 1), 30% at thread A, 15% at thread B and 20% at thread C. Each of these loads are considered as constant pressure distribution acting on threads A, B and C.

Special modified isoparametric elements were used to model the singularity existing at the crack tip, ref.[6]. The substructuring technique was used and the total number of degree of freedoms was 20000.

The main reason for running the Load Case III was to compare these results with the edge crack solutions. In elements near the crack tip the stresses are not shown because of the crack tip singularity. The constant pressure load on the thread, Load I, or the linear increasing load on the thread, case II, give comparable results.

STRESS INTENSITY FACTOR RESULTS

The method used to derive the stress intensity factor was the virtual crack extension method, ref. [5]. This method has been proved to be quite reliable by many authors, ref. [1], [9], comparing also experimental results. In Fig. 3, the results for the different crack lengths are shown for the Loads I/II. It can be seen that the highest values of the correction functions do occur with the smallest crack depth, 0.5 mm, and always at the surface. This effect is due to the thread depth. In the case studied the thread depth is 0.9 mm, against a crack length of 0.5 mm. When the crack depth is bigger than the thread, its influence is negligible. This behaviour confirms the influence of the stress raiser on the stress intensity factor.

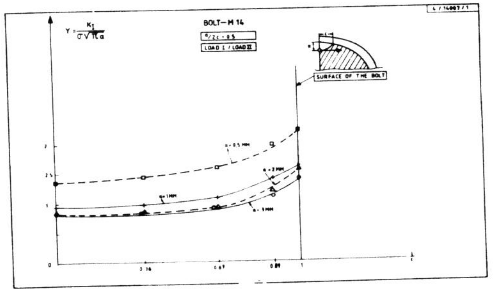

Fig. 3. Stress intensity solution for Load Case I/II

In Fig. 4 the results for the Load Case III are shown. These results are more uniform than the previous Load Cases I/II for the stresses, but the effect of the thread is the same at the smallest crack.

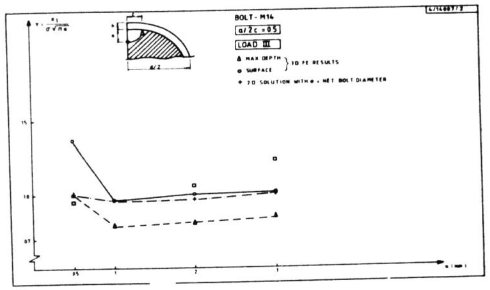

Fig. 4 Stress intensity solution for Load Case III

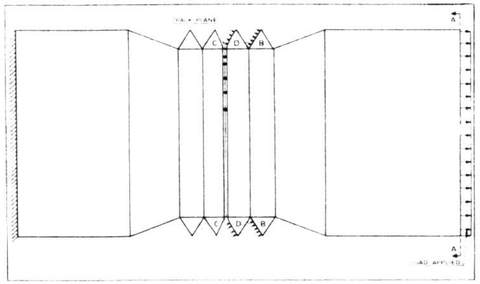

Fig. 1. Bolt geometry

b) Load Case II

Same as a), but with a triangular pressure distribution on threads A, B and C.

c) Load Case III

Only a uniform pressure applied at the section A-A.

The above-mentioned load conditions have been derived with the following assumptions:

i) the effect of a bolt screwing has been considered with a constant or triangular varying pressure load on the thread.

ii) no friction has been considered on the bolt due to the nut.

iii) the whole tooth flank has been considered as contact surface.

MATHEMATICAL MODEL

Because of the symmetry of the bolt geometry and assuming a crack symmetry in respect to the transversal plane, only half a bolt was idealized with a 3D finite element model, see Fig. 2.

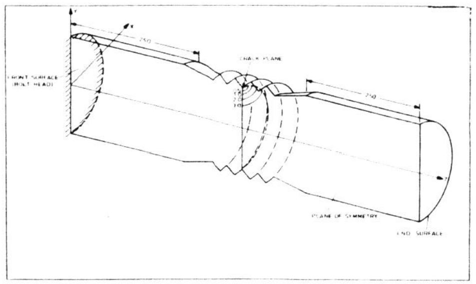

Fig. 2. 3D finite element model boundary conditions

In Fig. 5 the results are shown as a function of a/d. The stress intensity factor at the surface tends towards the value at the max depth as long as the crack is increasing, because big cracks are less influenced than small cracks from the loaded thread. This effect has been observed experimentally, ref [7]. When starting from a semi-circular initial flaw, the crack shape subjected to fatigue loads becomes flatter because the stress intensity factor at the surface is higher than at the maximum depth, so the crack growth at the surface is higher.

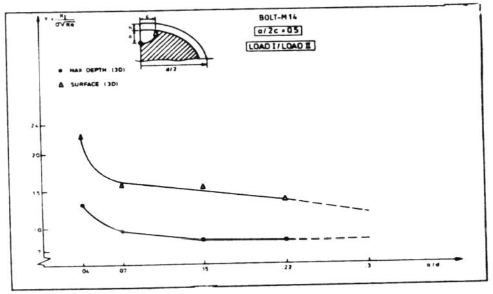

Fig. 5. Stress intensity solution as function of a/d.

COMPARISON WITH OTHER RESULTS

In Fig. 6 the influence of the loads acting on the thread can be seen at the maximum depth and at the surface of the bolt for every crack length. At the maximum depth, the stress intensity factor is not very much influenced by the load acting on the thread.

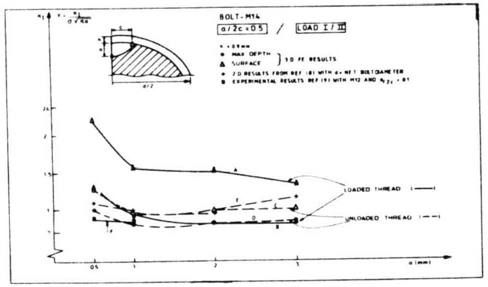

Fig. 6. Stress intensity solution load effort acting on the thread

For any other intermediate load redistribution on the threads, the stress intensity factor solutions could be interpolated. In the same figure the comparison with an existing 2D solution, ref. [2], of an edge crack in a bar is shown. It appears that the thread effect is not taken into account and this type of solution does not represent the load effect on the thread.

From ref. [3] some test results are available from M12 bolt where a big scatter has been observed. The bolts tested had no load applied to the thread and these test results are relative to the max crack depth. These results (curve F) compare well with curve D that are the 3D finite element results.

CONCLUSIONS

From the analysis performed and with the comparison made, the following conclusions can be derived also with reference to extension of these results beyond the M14 thread:

a) The stress intensity factor increases going from the maximum depth to the surface, for a surface flaw in the presence of a stress raiser.

b) There is basically no difference between Load Cases I and II. The cracks under the thread are not influenced by the shape of the load distribution on the thread, constant or triangular.

c) The correction function Y is increasing very steeply when the crack sizeis reducing especially at the bolt surface. This is due to the reduced crack length, which is influenced more from the notch of the thread because of the crack dimension (0.5 mm) being comparable or smaller thanthe thread dimension (0.9 mm).

d) If the pressure load acting on the thread should decrease from the values considered, the correction function should decrease to concide with the curve derived for a non-loaded thread.

e) In Fig. 6 it can be seen that the main difference in the correction function between loaded and unloaded threads is occuring at the surface. The values at the maximum depth between the loaded and unloaded thread present no big difference, and this difference decreases with the increasing of the crack depth because the influence of the stress field near the bolt surface is less important for the SIF values derived at the maximum depth.

f) The only difference expected on the correction function (Y) value due to different thread profile (Withworth, ISO) would be on the angle between the overall pressure resultant acting on the thread and the bolt axis. This different angle could originate higher or lower pressure effect on the crack.

g) Trends could be identified from the previous results for general cracked bolt problems:

   a. for decreasing a/d ratio the SIF tends to increase (0.1 a/d)
   b. for increasing thread depth in respect to the M14 (higher $A_{thread}/A_{net\ sect.}$) the SIF increases
   c. for higher pressure on the thread the SIF increases
   d. the SIF at the surface is normally about 40% higher than the SIF at the maximum depth for the Load I/II
   e. for 0.03 a/d 0.2 there is no big influence on the SIF distribution along the crack from different crack for shape 0.5 a/2c 0.35.

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