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Summary

Fasteners are widely used in aerospace and other industrial applications. Structural integrity analysis of such components is a critical necessity in many of the applications. The present paper describes some recently obtained stress intensity factor solutions for cracked threaded members and for cracked fillet areas under bolt heads. The cracks were assumed to be thumbnail shaped and to originate at the thread roots or fillet radii. The assumed aspect ratios were based on observed shapes from crack growth tests. The tests were conducted on A286 steel, Ti-6Al-4V titanium alloy and 7075-T73 aluminum alloy. Crack growth was measured using marker bands that result from changing the load level after a certain number of cycles. The measured crack growth rates were converted to stress intensity factors using certain principles of similitude. Three dimensional finite elements were used to verify the solutions. Finite element analysis was also used to compute the stress concentration factors at the thread roots and fillets. A distinction was made between rolled and cut threads. In the case of rolled threads or fillets, the residual stresses present caused a reduction of the stress intensity factor for small cracks. In the case of machined threads or fillets, the stress concentration factor at the thread or fillet root governs the magnitude of the stress intensity factor. Specific solutions were constructed and coded in for standard aerospace bolt sizes, but provision is made for other sizes that may be applicable for general industrial use. The solutions are valid for metric as well as US Customary sizes. These solutions were developed for implementation into the NASGRO 3.0 software. NASGRO is a state-of-the-art software package for fatigue crack growth and fracture mechanics analysis.

Contents

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1 Introduction

Fasteners are widely used in aerospace and other industrial applications. Structural integrity analysis of such components is a critical necessity in many of the applications. During both the design and service phases, structural integrity assessments typically use the damage tolerance approach. In this approach, flaws that are at the threshold of detection by nondestructive evaluation (NDE) methods are assumed to be present in the structure at the worst possible location. The residual strength of the structure in the presence of the assumed flaw should be adequate for safe operation. In addition, the propagation of such a flaw subject to service loads until it reaches a size that leads to catastrophic failure needs to be characterized. Central to such characterization is the knowledge of the stress intensity factor for the assumed crack geometry. The present paper is concerned with constructing stress intensity factor solutions for cracked threaded members and for cracked fillet areas under bolt heads. These solutions were developed for implementation into the NASGRO 3.0 software. NASGRO is a state-of-the-art software package for fatigue crack growth and fracture mechanics analysis. A brief review of the available solutions for threaded fasteners is first presented. Subsequent sections deal with the methods used to develop the solutions. Finally, the engineering models formulated based on these solutions are presented.

2 Literature Survey

Early studies (Refs. 1-3) of cracks in solid cylinders form the basis for estimating stress intensity factors for cracks in the shank area of bolts. Experimental verification of these solutions was conducted by Forman and Mettu (Ref. 4). The stress intensity factor solution for a crack in the threaded area is a more complicated problem and few good solutions exist. The fillet area under the bolt head can be treated similar to the threaded area by using suitable stress concentration factors. Liu (Ref. 5) presented a comprehensive review of the available solutions for threaded bolts. In his review, he compared the available analytical solutions with experimental results for tension and bending loads. None of these solutions takes the interaction between the nut and the bolt into account. The present study aims to represent the loading more accurately by considering the bolt/nut assembly for modeling purposes in both the analytical and experimental approaches.

3 Experimental Method

The experimental work described in this paper was conducted by de Koning, Lof and Schra (Ref. 6). In order to simulate realistic loading conditions, threaded bolt/nut assemblies loaded in tension and bending were used. Aerospace quality bolts M8*1.00 mm and M12*1.25 mm made of three different materials, A286 steel, Ti-6Al-4V titanium alloy and 7075-T73 aluminum alloy were used. The nut was made of steel. Constant amplitude loading was applied. To measure the crack growth, marker bands were induced by reducing the load level serially at predetermined numbers of cycles. While the constant amplitude loading was applied at a stress ratio of R=0.1, the marker loads were applied at a ratio of R=0.7. The mean load level was kept constant. During some of the tests, the level of bending stresses in the bolt shank was measured using strain gauges. These measurements were made at the beginning of the test, both before the fatigue crack was initiated and during the crack growth phase, to ensure that the bending stresses are small. The maximum loads applied for these tests were 23.5 KN and 9.7 KN for the M12 and M8 bolts respectively. The elliptical starter notch was prepared using electric discharge machining with a depth of 0.5 mm and an a/c ratio of 0.6.

The stress intensity factor (K) along a crack front in the bolt is determined using a principle of similitude. According to this principle, it is assumed that for identical environmental conditions, the stress intensity factor is the same if the fatigue crack growth rate is the same, regardless of geometry and loading conditions. Using the marker bands mentioned above, the crack size can be measured at regular intervals from the fracture surface. Knowing the corresponding cycle count, the crack growth rate vs crack size can be plotted. Using a cylindrical bar specimen, a curve of crack growth rate vs stress intensity factor range (dc/dN vs ΔK) can be generated, because the stress intensity factor solution is known for this specimen (Ref. 7). Using these two plots, the K vs c relation for the cracked bolt can be deduced as shown in figure 1. The same procedure is repeated at various points along the crack front.

The fatigue tests on the notched bolts with cut threads showed quite a different behavior compared to the bolts with rolled threads. For bolts with rolled threads, the crack aspect ratio remained at about a/c=1 and for machined fillets, the crack aspect ratio is found to be close to a/c=0.645. A detailed account of the behavior of various types of starter notches from cut and rolled threads is given in reference (Ref. 6). Based on observations of the marker bands on the fracture surfaces, some specimens were selected for determination of the stress intensity factors.

4 Finite Element Analysis

A portion of the finite element analysis described here was first reported in reference (Ref. 6) and the rest was conducted recently. The load transfer between the threaded bolt and the nut was analyzed using the finite element method. This method was also used to compute the stress intensity factor distribution along the crack front. Full three-dimensional meshes of nut and bolt were used in the analysis. Quadratic isoparametric 20-noded brick elements were used. Elements adjacent to the crack front were shrunk to form wedge-shaped elements to obtain the square root variation of displacements near the crack tip. The commonly used shifting of mid-side nodes to the quarter-point position was used. The stress intensity factors were extracted using de Lorenzi’s method (Ref. 8). This method uses the virtual crack extension to first compute the energy release rate and then the stress intensity factor assuming plane strain conditions. The discretized bolt length was seven times the pitch. Four threads under the nut and three threads on the free shank portion of the bolt were chosen for modeling. A typical finite element mesh had about 7000 elements. The contact surface of the nut and bolt is simulated by rigid coupling of displacements of all nodes on the contact surface. This implies that friction is not modeled. The outer surface of the cylinder is modeled as a cylinder rather than as a hexagonal pyramid. Different a/c ratio’s were modelled according to the ratio’s observed on the fracture surfaces of the specimens tested (a/c=1 for rolled threads, a/c=.645 for cut threads).

The p-version finite element software “STRESS CHECK” was used to compute the stress concentration factors at the root of a fillet. The stress concentration factors for a given fillet radius to diameter ratio, r/D is shown in table 1.

5 Implementation in NASGRO

The following three crack configurations have been formulated for engineering use and implemented into NASGRO 3.0 as described in the reference manual (Ref. 9).

SC08 – Surface Crack in Bolt Thread (Thumbnail Crack)

Figure 2 below shows the geometry and loading. Stresses S_0 and S_1 (see Fig. 2) are the remote applied stresses. Tables 2 lists values of normalized stress intensity factors F_0 and F_1. These factors are defined as $F_0 = K_I/(S_0\sqrt{\pi a})$ and $F_1 = K_I/(S_1\sqrt{\pi a})$. The parameter f_x is defined as $f_x = [1+1.464(a/c)^{1.65}]^{-1/2}$.

SC13 - Surface crack from cut fillet under a shear bolt head

Values of the normalized stress intensity factors F_0 and F_1 from table 2 and the stress concentration factors from table 1 are used.

SC14 - Surface crack from rolled fillet under a tension bolt head

Values of F_0 and F_1 from table 2 are used for this crack case. For the machined fillet, a/c=0.645 is used and for the rolled fillet, a/c=1.0 is used (see sections 3 and 4). In this case, the fillet radius is assumed constant (r/D=0.1).

6 Summary

Stress intensity factor solutions were developed for cracked threaded members and fillet areas under bolt heads. The cracks were assumed to be thumb-nail shaped (with suitable aspect ratios) originating at the thread roots or fillet radii. The assumed aspect ratios observed shapes from crack growth tests conducted on A286 steel, Ti-6Al-4V titanium alloy and 7075-T73 aluminum alloy. The measured crack growth rates were converted to stress intensity factors using principles of similitude. Three dimensional finite elements were used to verify the solutions. Finite element analysis was also used to compute the stress concentration factors at the thread roots and fillets. A distinction was made between rolled and cut threads. In the case of machined threads or fillets, the stress concentration factor at the root governs the magnitude of the stress intensity factor. Specific solutions suitable for engineering use were constructed and coded in for standard aerospace bolt sizes into the NASGRO software. Provision was also made for other sizes that are applicable for general industrial use.

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Table 1 Stress concentration factors for a bolt in tension and bending

r/D	0.005	0.01	0.015	0.02	0.025	0.03	0.035	0.04	0.045	0.05.
K_t	10.8	7.89	6.55	5.73	5.17	4.77	4.48	4.19	3.97	3.79
r/D	0.055	0.06	0.065	0.07	0.075	0.08	0.085	0.09	0.095	0.10
K_t	3.63	3.49	3.37	3.26	3.16	3.07	2.97	2.91	2.84	2.78

Table 2 Stress intensity factors for a bolt in tension and bending

	F_0		F_1	
a/D	a/c = 0.645	a/c = 1.0	a/c = 0.645	a/c = 1.0
0.0	K_t / f_x	1.00	K_t / f_x	0.60
0.05	-	0.84	-	0.54
0.1	0.95	0.76	0.61	0.48
0.2	0.90	0.65	0.54	0.37
0.3	0.98	0.59	0.55	0.31
0.4	1.29	0.62	0.64	0.30
0.5	2.05	1.0	0.84	0.50

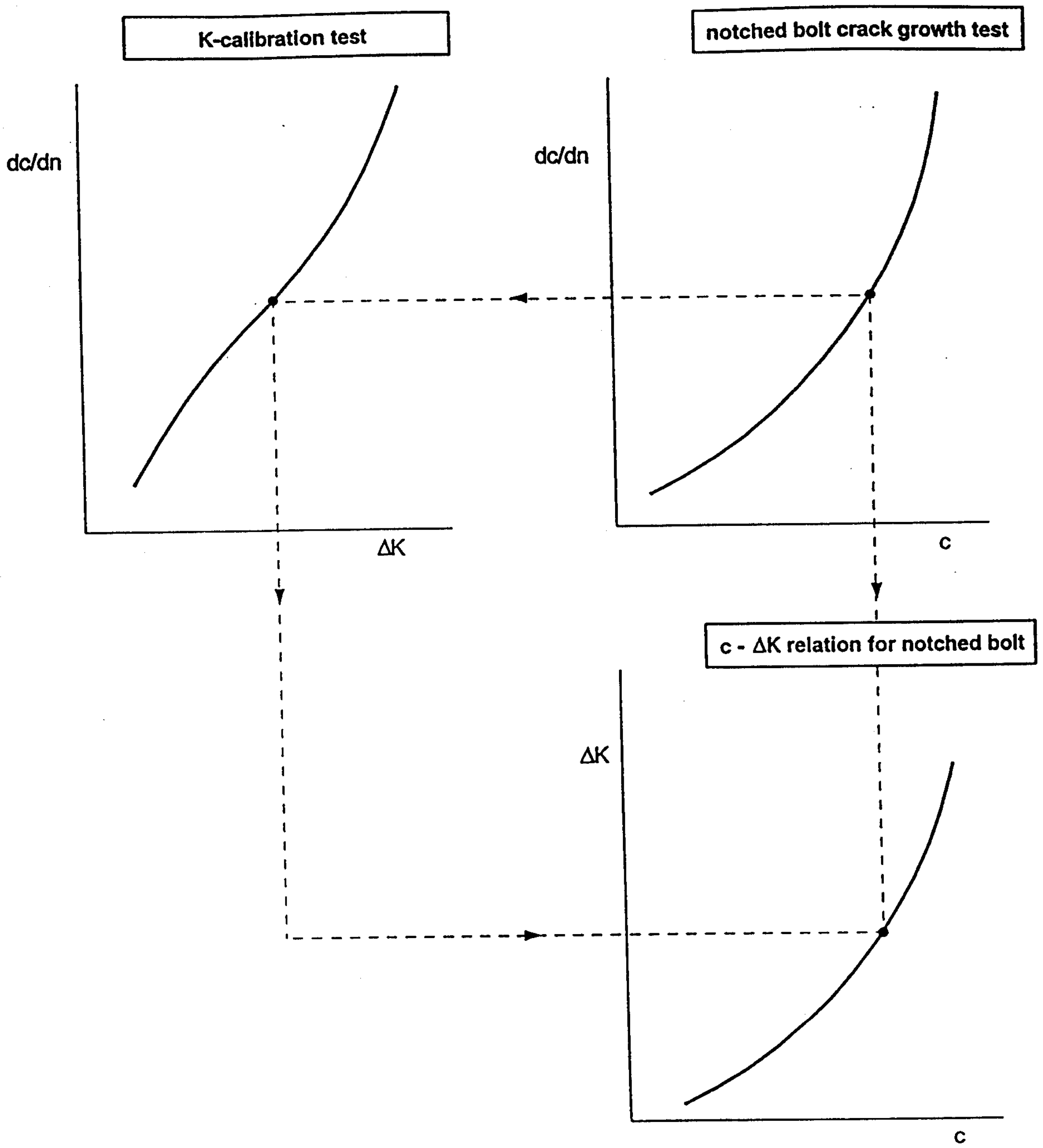


Fig. 1 Schematic of the derivation of K vs c for cracked bolt

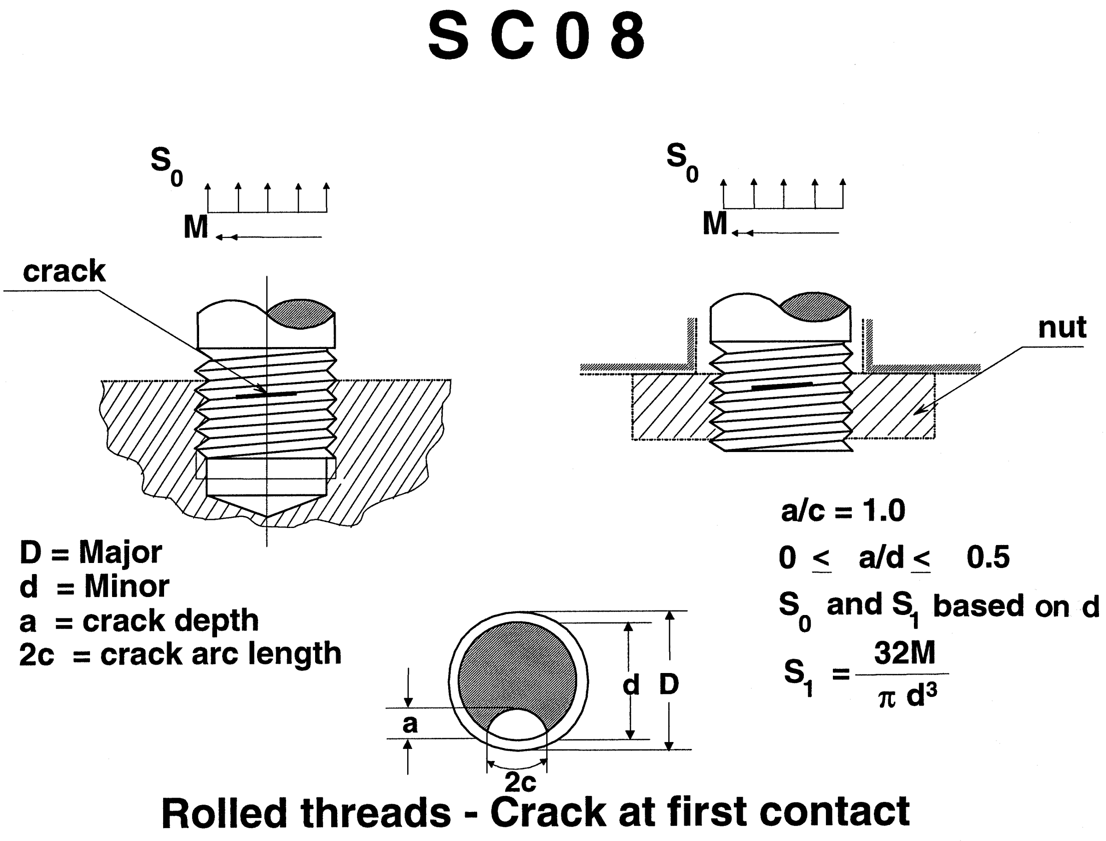
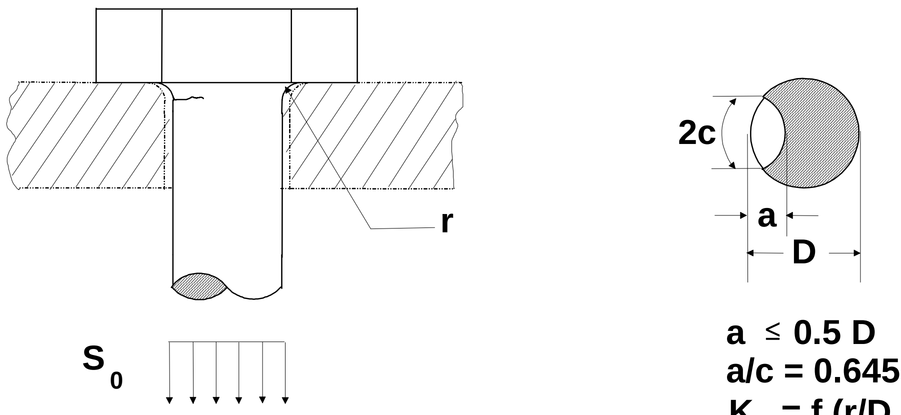


Fig. 2 Crack geometry SC08

S C 1 3



$a \leq 0.5\,D$
$a/c = 0.645$
$K_T = f\,(r/D)$

Shear or Machine Bolt-Machined Fillet

Fig. 3 Crack Geometry SC13: Shear Bolt

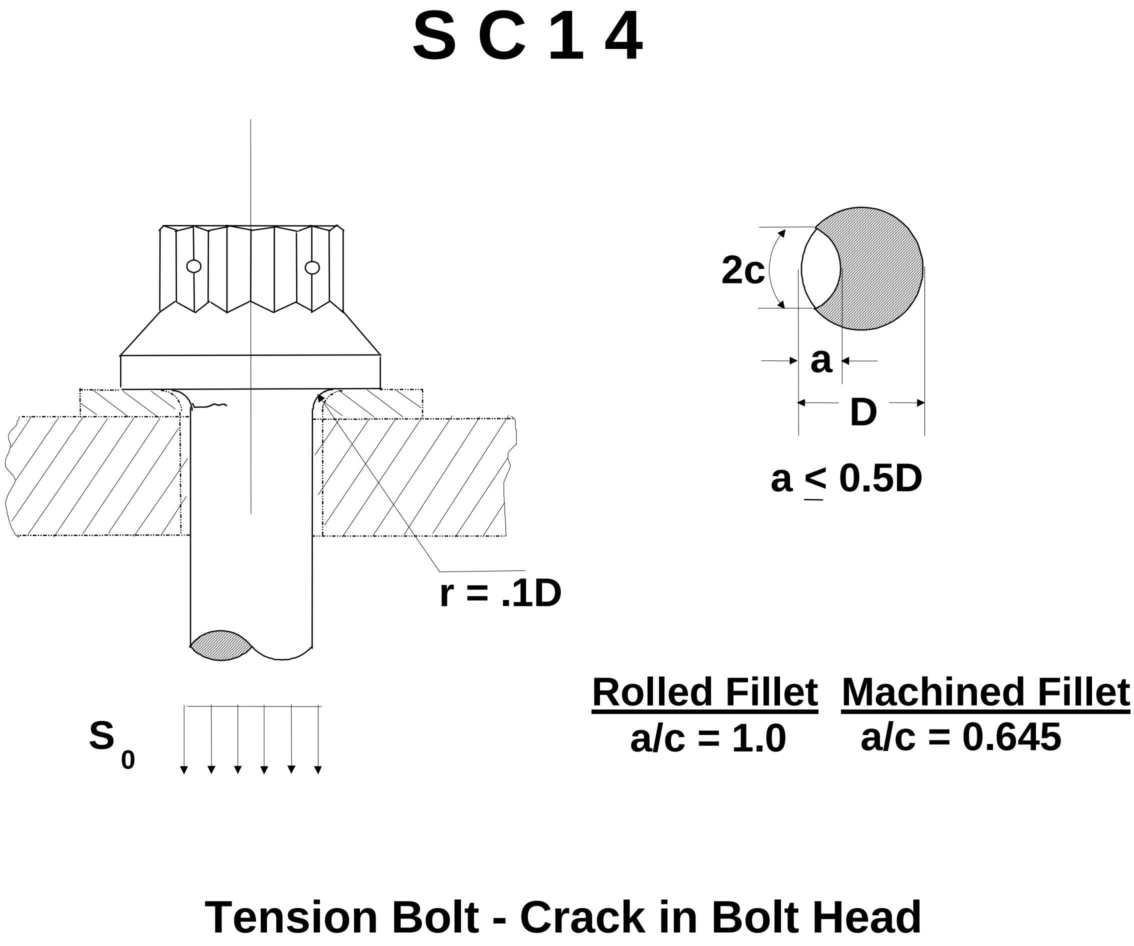


Fig.4 Crack Geometry SC14: Tension bolt