Open Hole Testing Methods for Different Materials: A Review

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Abstract. In service failure of the fastened structures is an important concern for the automobile and aerospace industries. The failure of these structures is mainly due to the presence of holes which act as stress concentration sites. These localized stress concentration sites are responsible for crack initiation and propagation. Open hole tests of the structural component under tensile stresses and cyclic loading can help to predict component failure. Studies based on the effect of hole fabrication technique, hole size, specimen dimensions, nature of material, type of loading and strain rate on the tensile and fatigue strength of the component, helps in establishing the failure mechanisms for the component. This review is to understand different open hole tests required to predict the tensile and fatigue strength of aluminium alloys and composite laminates used particularly in automobile and aerospace industries.

1. Introduction

In past decades, automobile and aerospace industry have seen evolution of different materials from steels to aluminium alloys and composites, with the primary aim to reduce structural weight as well as cost without compromising on the mechanical properties. These composite/alloy parts are often required to be joined with other components of the structure. Conventionally, drilling of holes is the most common method used to create holes in the component for mechanical fastening, due to the simplicity involved. However, the hole created during such fastening process creates huge stress concentrations in nearby region, thereby deteriorating the overall strength of the structure. This makes open hole testing of the structural component an important part of the examination process.

Stiffened structures used in aerospace applications are generally subjected to cyclic loading and high tensile stresses. Hence, these structures should be light weight, stiff, strong and less sensitive to fatigue. Carbon/glass reinforced epoxy/metal matrix composites and aluminium alloys (2000, 6000 and 7000 series) are commonly used in development of these structures. Presently, a major portion of the aircraft structure is made using aluminium alloys due to its high strength to weight ratio and worldwide availability. 7000 series are typically used for high strength applications while 2000 series are used for fatigue applications since these alloys are more damage tolerant [1]. For instance, AA 2024-T3 sheets are used as fuselage/pressure cabin skins while high strength 7055-T7951/7150-T7651 are used as upper wing covers in aircraft [2]. Lately, lithium mixed aluminium alloys have been used considering the advantage of low density lithium. The 2199 Al-Li alloy sheets are used for aircraft fuselages and lower wing skin applications [3]. Other than aluminium alloys, laminated composites are also being used in aerospace and automobile applications due to their excellent strength and stiffness to density ratios. Both carbon and glass fibre reinforced composites are being commonly used in aerospace and automobile applications. In laminated composites, different oriented fibre sheets are stacked in sequence to achieve structure with better properties in loading directions without adding up extra material and hence weight. A380 commercial aircraft constitutes about 20-22% weight of composites extensively glass-fibre reinforced aluminium alloy composite (GLARE). GLARE laminates find its application in the front fairing, crown and side panels, upper fuselage shells...
and upper sections of forward and aft upper fuselage [4]. It becomes clear from above discussion that to predict strength of a fastened structure requires open hole testing under different types of loading like tensile, compressive and fatigue as experienced by them during service. Parameters most affecting a open hole test are hole fabrication technique, hole and specimen dimensions, material, type of loading (tensile, compressive, fatigue) and strain rate. Open hole study can be used to understand the mode of fracture, probable sites for crack initiation and propagation and local stress concentration and hence predict component strength.

The purpose of this review is to understand the effect of open hole on the fatigue and tensile strength of the structural component. Various open hole test methods have been discussed to study failure at fastened joints in aluminium alloys and laminated composites used predominantly in aerospace industry.

2. Materials and Methods

2.1 Specimen Preparation
Sample preparation is an important part of the open hole testing process. This section discusses on the specimen preparation for open hole tensile, compressive and fatigue tests for laminated composites and metal alloys. Specimen preparation involves cutting the specimens from the component as per ASTM standards, followed by drilling of holes and finally polishing. Table 1 mentions the ASTM standards used for metal alloys and composites for tensile, compressive and fatigue open hole testing. Different specimen geometries for ASTM mentioned in Table 1 are shown in Figure 1.

| Material       | Tensile | Fatigue       | Compression |
|----------------|---------|---------------|-------------|
| Aluminium Alloys | E8      | E606*/E647*   | E9          |
| Composites     | D5766   | D7615         | D6484       |

*E606 – Test Method for Strain Controlled Fatigue Testing
*E647 – Test Method for Measurement of Fatigue Crack Growth Rate

2.1.1 Sample Cutting
Different sample cutting methods can be used to cut the specimen to required dimensions as laser cutting, plasma cutting, electric discharge machining (EDM) and water jet cutting. The choice of method depends on the type of material to be fabricated. For example, laser cutting is preferred to cut laminated composites because of its precision cutting and no pulling of fibers. Plasma cutting and EDM are used only for conductive materials. On the other hand in terms of convenience water jet cutting is most preferable method.

2.1.2 Hole Drilling
For open hole testing, a centrally placed open hole has to be created on specimen as shown in Figure 1 (d). Technique used to create this hole can have a huge impact on the component strength due to increased chances of generation of stress concentration sites. Cold expansion technology helps in solving this issue by having fewer stress concentration sites. Some of the widely used cold expansion techniques have been discussed here.

Hole Edge Expansion technique as illustrated in figure 2(a) uses a high hardness tapered indenterto be extruded/hammered into the drilled open hole under the uniaxial force. Initially, plastic deformation takes place near the hole edge and then a subsequent region of compressive residual stresses is formed. As the middle part of the plate does not get strengthened by this technique, therefore this technique cannot be employed for thick plates and is limited to sheets only. Many times, multiple insertions are needed to be done to achieve the desired stress relieving.

Direct Mandrel Expansion is widely used method for producing anti-fatigue structural parts. A pre lubricated mandrel shown in figure 2(b) is inserted from entrance side and removed from other side to the extent to ensure permanent plastic deformation. Upon removal of the mandrel the surrounding
material tries to get back to its original position creating a proper distribution of compressive residual stresses and smoothing the hole surface.

Figure 1. Specimen Geometries for ASTM mentioned in Table 1. (a), (b), (c) represent specimen geometry for alloys. (d) represent specimen geometry for composites. *For E9, L/D ratio of short, medium and long specimens are 0.8/2.0, 3.0 and 8.0/10.0. #All dimensions are in mm.

Ball Expansion uses a pre-lubricated and oversized hard steel ball inserted in the open hole from entrance side and removed from other side as shown in figure 2(c). Due to local interference area between hole and ball surface, friction generated is less compared to other mandrel techniques. Therefore, this method is applied only for small holes. One drawback is that it produces localized residual tensile ring on the entrance surface of the mandrel which reduces anti fatigue effect as compared to other expansion processes.

Figure 2. Different Cold Expansion Techniques [5] 
(a) Hole Edge Expansion (b) Direct Mandrel Expansion (c) Ball Expansion (d) Split Sleeve Expansion

Split Sleeve Expansion technique overcomes the problem of surface damage occurred during the cold expansion process. In this technique, the split sleeve is placed over the mandrel and the mandrel/sleeve assembly is inserted into the initial open hole as illustrated in figure 2(d). Permanent plastic deformation occurs when the other part of the mandrel with increasing diameter passes through the sleeve. After the mandrel is withdrawn from the sleeve, split sleeve is removed from the expanded hole leaving a desired compressive residual stress. Compared to other techniques, split sleeve
technique is more widely used in aerospace industries, especially in bad openness connection of aircraft assembly.

2.1.3 Polishing
During sample cutting and drilling operations itself, various localized stress concentration sites can be introduced in the specimen which can influence the accuracy of the open hole test method. To reduce the effect of localized stress concentration sites, sample polishing has to be done carefully using sand paper to smoothen the surface and edges so as to remove any unwanted notches in the sample.

2.2 Open Hole Tensile and Compression Test
Open Hole Tensile and Compressive testing can be performed using Universal Testing Machine. In tensile testing, coupon is fixed to the test apparatus between the plates and then a uniaxial force is applied to the coupon by separating the crossheads of the machine under specific strain rates. Similarly, in compression testing, load is applied to the specimen by moving the crossheads towards each other. Data from the tests can be used to find tensile and compressive strength respectively along with other properties.

2.3 Open Hole Fatigue Test
Open Hole Fatigue testing of the coupons can be performed using a fatigue testing machine when coupon is loaded to pre determined stress and then unloaded to either zero load or an opposite load. The cycle of loading and unloading is repeated either up to the pre determined number of cycles or until the failure of the material.

3. Discussion
Hole used to mechanically fasten two components acts as a stress concentrator, where cracks can easily initiate, especially in thin walled structures used in aviation and automobile sector. The failure can occur when strain at the edge of holes reaches ultimate local strain capability as illustrated in figure 3(a) [6].

For ductile metal/alloys, under uni-axial tensile loading the yielding begins from the points of maximum stress concentration (point A, figure 3(a)) which is generally situated at the hole boundary in a direction perpendicular to tensile loading. With further increase in loading, the yielding progresses at an approximate angle of about 45° degrees with respect to loading direction. The plastic region thereby formed shown in figure 3(b), varies depending on the deformation behavior of the material and stress-strain relationship. Mortezahave done a detailed analysis on internal angle having several holes made in 7075 Al alloy used in Airbus A300 for a crack that was detected at length 28mm resulting in reduction of strength below the allowed value. Using Von-Mises criterion they proved that the stress was maximum around the fastener holes and has resulted in the crack propagation in between two holes [7].

Hole fabrication technique affects the durability of material under high stresses and cyclic loading. Hole fabrication using drilling technique cause large geometrical discontinuities which are a source of localized stress causing early failure of material during loading. Investigators have found that a large
number of accidents are caused by fatigue failures that are initiated from fastener holes. Statistics show that in aging planes, fatigue failures of fastener holes account for 50-90% of fractures [8]. In order to improve on fatigue life of structure, several new techniques of hole fabrication have been invented. Cold expansion of holes is one such widely used technology for creating a plastic deformation zone. Here, a drilled hole is subjected to elastic-plastic deformation which generates compressive residual stresses around the hole. These residual stresses decrease stress concentration around the hole thereby preventing the premature fatigue failure of the material. Development of plastic zone and increase in hole size due to cold expansion is illustrated in figure 4. Yasniy et al. studied the effect of cold expansion and diameter of holes on stress distribution, fatigue crack nucleation and its growth under uniaxial cyclic loading for 2024-T3 aluminium alloy plates [9]. They observed with increase in degree of cold expansion the number of loading cycles increased due to changed periods of initiation and propagation of fatigue cracks.

![Figure 4. Crack Extension by Cold Expansion Technology](image)

- length of crack along thickness;
- crack length on entrance face of mandrel;
- crack length on exit face on mandrel.

Metal matrix fiber reinforced composites can fail due to numerous modes of damage. Damage is primarily due to fiber breakage, matrix cracking, matrix plastic deformation, delamination, and fiber-matrix debonding. The sequence and combinations of the failure mechanisms depend on many variables as constituent properties, fabrication process, loading conditions, specimen geometries and heat treatments. However due to the complexity introduced by combining constituent elements to form a composite, material behaviours and failure progressions; a detailed experimental investigation is always necessary to fully characterize the failure. Therefore, thorough analytical work has to be performed to predict elastic and plastic stress concentration factors, stresses around the periphery of the notch, failure loads, and residual stresses. Damage progression in the form of fiber-matrix debonding, fiber failure, matrix cracking, and plasticity can be studied using optical and scanning electron microscopy.

Newaz and Majumdar analyzed crack initiation around holes in a unidirectional, SCS-6/Ti-15-3, metal matrix composite under monotonic and fatigue loading [10]. They observed continuous, through the thickness, cracks emanating at the periphery of the hole at 65° to 72° from the load axis under fatigue loading which primarily initiated due to shear stress. Under monotonic tensile loading, fracture occurred at 90° from the load axis at the point of maximum stress concentration. Here yielding initiated at the four symmetric locations (65°-72°) but in absence of cyclic loading, the slip was unable to intensify. As load was increased, the fiber at the 90° experienced large tensile stress ultimately reaching a point where the fiber failed causing failure of the composite. Johnson and Naik characterized fatigue damage initiation and growth of SCS-6/Ti-15-3 with centre holes and double edge notches at room temperature[11]. They observed that fiber matrix debonding and matrix cracking greatly reduces the stress concentrations around the notches and the predicted elastic stress concentration factors are least 25 percent too high once local, near hole, fiber matrix debonding occurs.

The width-to-diameter ratio of hole also plays a significant role in determining the strength of a specimen. To understand effect of hole size on structure strength several studies has been performed by researchers. Lawcock et al. observed around 40% reduction in strength for unidirectional Carbon fiber reinforced aluminium laminates with circular holes. Using average stress criterion, they...
evaluated the variation in residual strength due to holes of different diameters. Yuan et.al studied open hole tensile behaviour of carbon fiber reinforced aluminium laminates and observed that with increase in hole diameter, specimen failed at lower strain. This phenomenon was attributed to the fact that bigger hole could produce higher stress intensity factor, leading to the reduction of strength and brittle failure behavior in the specimen [12]. In their study, the 0°/90°/0° showed neat and perpendicular fracture to loading direction while 45°/0°/45° exhibited diversified failure in which CFRP layers were pulled out of laminate as a consequence of delamination and matrix cracking. Thus 0°/90°/0° exhibited lesser failure strain than 45°/0°/45°. Failure sequences showed that prior to failure, aluminium yielding occurred and also the stress in material increased with increase in hole size.

Many applications demand use of elevated temperatures. Components having fastened holes are more susceptible to failure at these temperatures. For example, Johnson and Pollock characterized unnotched SCS-6/Ti-15-3 under strain controlled testing at room temperature and 650°C [13]. At 650°C they observed significant amount of time-dependent deformation associated with the matrix material which was negligible at lower temperatures. At 650°C the matrix yield strength was so low that all laminates exhibited ultimate strengths significantly greater than that of the matrix alone. This is one of a major reason why fiber reinforcement is necessary for elevated temperature applications.

Generally, commercial testing of a structural element requires large number of specimens to be physically tested under certain conditions in a specified time. However this process is time consuming and involves huge cost. In order to reduce costs, theoretical analytical tools can be used to predict the damage and failure in open hole tests. Such predictions not only reduce the number of testings but also enable one to incorporate material’s behaviour early in the design. These tools uses fracture mechanics, point and average stress criteria and a progressive damage modelling [14]. Amongst these, progressive damage modelling is most relevant as it provides information on sub-critical damage and can be applied to basic tests for material properties, without the need to calibrate quantities as characteristic distances. The effects of different configurations as well as change in parameters can be easily predicted by modelling tools and then compared with the experimental results. Finite element method (FEM) can capture variations in the failure as well as absolute values of strength [15]. To get accurate results, FEM must take into account interaction between intra-ply splits, intra-ply delamination and fiber failure. Victor Achard et.al applied Discrete Ply modelling for open hole testing of low velocity and low energy impacts on laminates stacked with unidirectional plies, and observed through the ply cracks responsible for damage propagation [16]. By refining the mesh near the hole, their results showed good agreement between the experimental and numerical results and gave good prediction of ultimate tensile stresses and failure patterns.

4. Conclusion

Various theories described that the vicinity of holes acts as a source of maximum stress concentration and can lead to in service failure of the structural component. This makes open hole testing an important part of the examining process for components used in aerospace and automobile industries. Failure mechanism depends on the type of material and loading conditions and mostly initiate at 90° to the tensile loading in hole’s vicinity and propagates further depending on the stress-strain relationship of the material. In composites, the orientation of fiber has a huge impact on the strength. Studies showed that 90° orientation fiber with respect to matrix showed lesser failure strain, neat and perpendicular fracture to loading direction as compared to 45° orientation fiber. To reduce stress concentration around holes, various cold expansion techniques have been studied. To lower the effort and cost of preparing large number of specimens, theoretical analytical methods can be used which gives similar result compared to experimental results.

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