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An engineering point of view about fatigue of polymer matrix composite materials

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Abstract

High performance polymer composite materials reinforced by long fibres have a reputation for good fatigue behaviour. Let us note, in connection with the above statement, that the substitution of metals by composite materials is a success for aeronautical applications. However, fatigue of composite materials is still an important problem for an engineering point of view, because its nature is basically different of fatigue of metals. This paper is devoted to a comparison of fatigue damage between metals and composite materials.

Keywords: Composite materials; Fatigue; Substitution of metals; Design

1. Basic remarks on fatigue

The word of "composite materials" covers a large range of materials. Obviously, it is difficult to get a general approach of the fatigue behaviour including polymer matrix, metal matrix, ceramic matrix composites, elastomeric composites, Glare, short fibre reinforced polymers and nanocomposites.

For this reason, some limitations are needed. It is also useful for the engineer to compare carefully the fatigue of composite materials to the fatigue of metals because the design of a component made in composite material is very often the result of a metal substitution. It is of interest to remember the famous sentence from professor Tsaï: "Think composite".

As it is said by Harris in "Fatigue in Composites" [1] it is "wrong to assume, a priori, that there are some universal mechanisms by which fluctuating loads will inevitably result in failure at stresses below the normal monotonic failure stress of the material". The fracture in high performance composite material structures is of a quite different nature from that of metallic components. Failure, due to fatigue, is to be feared much less in the first case than in the second.

Metallic fatigue has been intensively studied for more than 150 years since the Whoëler's pioneering work. Nowadays, the metallic fatigue is approached using some well-established concepts:

- Low cycle fatigue from L. Coffin and Manson
- Mega cycle fatigue from A. Whoëler
- Giga cycle fatigue from C. Bathias [2]
- Crack propagation from P. Paris

The situation for composite materials is quite different for which the giga cycle fatigue regime is totally unknown. The composite material SN curves are usually between 10^3 and 10^6 cycle, not more. It must be pointed out that the damage tolerance approach is not so fruitful for composites than for metals. The delamination, which in the first approximation implies flaws in the plane, can be treated by fracture mechanics using the modified Paris law. More difficult is to apply fracture mechanics to notched laminated plates. In some cases where a quasi-isotropic lay-up exists, it is always possible to use fracture

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mechanics to predict the failure of notched plates. However, where a strong orthotropic effect appears, fracture mechanics criterion does not work very well. Other criteria such as Nuismer and Whitney approach [3] or damage mechanics models [4] are recommended. Thus, a specific modeling is to be done.

In spite of the lack of the basic knowledge, composite materials have taken a prominent position in the engineering systems starting from the aircraft industry. High performance composite materials, reinforced by long fibres of carbon, glass, boron or Kevlar have a reputation for good fatigue behaviour. Aside fear the specific properties of these materials; their exceptional fatigue strength is responsible for their success in the aeronautic industry. It is interesting to note, in connection with the above statement, that the substitution of aluminium alloys by carbon and glass fibre composites in helicopter propeller blades improved their durability in crucial conditions. Thirty years ago, it was common for users of CFRP involved in Airbus program to express the belief that these advanced materials did not suffer from fatigue. Today, it is assumed by certain experts including Harris [1] that fatigue of CFRP should be one reason among others, explaining the crash of AA 587 on November 2001, near New York airport.

In fact, the ratio, S_D/UTS, between the fatigue strength S_D in tension–tension and the ultimate tensile strength UTS is always greater than 0.4 and can reach 0.9 for CFRP, values comparable to those found for metals, less than 0.5, and only 0.3 for aluminium alloys [5]. Indeed, the fatigue resistance of composites depends of the stacking sequence. It means that for many aeronautical components made in carbon fibre composite, fatigue resistance is not a key parameter for design. For example, the first parameter to design a vertical tail made in carbon-epoxy is not fatigue. The vertical stabilizer for an aircraft is designed facing the load in the standard crash conditions, which is assumed to be more severe than that of the service cyclic loading.

In any case, this exceptional behaviour of high performance composite materials does not mean that they are totally sheltered from fatigue. In reality, the endurance of composites varies according to the type of fibres, the resin and the lay up: the fatigue strength of carbon fibre is much better than that of glass fibre; epoxy resin is better than polyester, and so on. Let us note that, in addition, composites are damaged in fatigue under shear or compression loading much more than metals. For example, the simultaneous damaging in tension, compression and shear of a composite material under cycling bending renders the phenomenon complex. Finally, it is well known that the fatigue resistance of composite materials is much lower in compression–compression than in tension–tension. It is the contrary for metallic alloys. Starting from those observations, it is of interest to point out some drastic differences between metals and high performance composites in regard with the need of the designer.

2. Drastic differences between the fatigue of composites and metals

Many differences occur at the microscopic level and at the macroscopic level to explain the fatigue behaviour of high performance composite materials. The main aspects are sum up as followed.

2.1. Damage at the microscopic level

In metals, the fatigue damage is strongly related to the cyclic plasticity that is to say the dislocation mobility and slip systems. Due to the environment effect and the plane stress states, the initiation of fatigue damage is often localized near the surface of metals.

In polymer matrix composite materials the fatigue damage is not related to plasticity. Considering only polymer-matrix composites reinforced by long fibres, it is acknowledged that the first damage that appears under loading is matrix cracks, before the fracture of the fibres. These are micro cracks with an initial thickness of one layer, and their presence constitutes the initiation of damage. Propagation will develop next, by a multiplication of cracks building to a critical density [6,7] and resulting in the development of delamination, until the eventual fracture of the fibres, should that arise. Reifsnider proposed the existence of a critical crack density for a given type of layer [6].

At the mesoscopic level, the fatigue damage propagation in metal is a single crack perpendicular to the tension loading. This fatigue crack tip is surrounded by a plastic zone whose radius is of the order of 100 μ. In composites materials, the fatigue damage is multidirectional and the damage zone, much larger than the plastic zone, is related to the complex morphology of the fracture [8] (Fig. 1).

2.2. Remark on the endurance curve

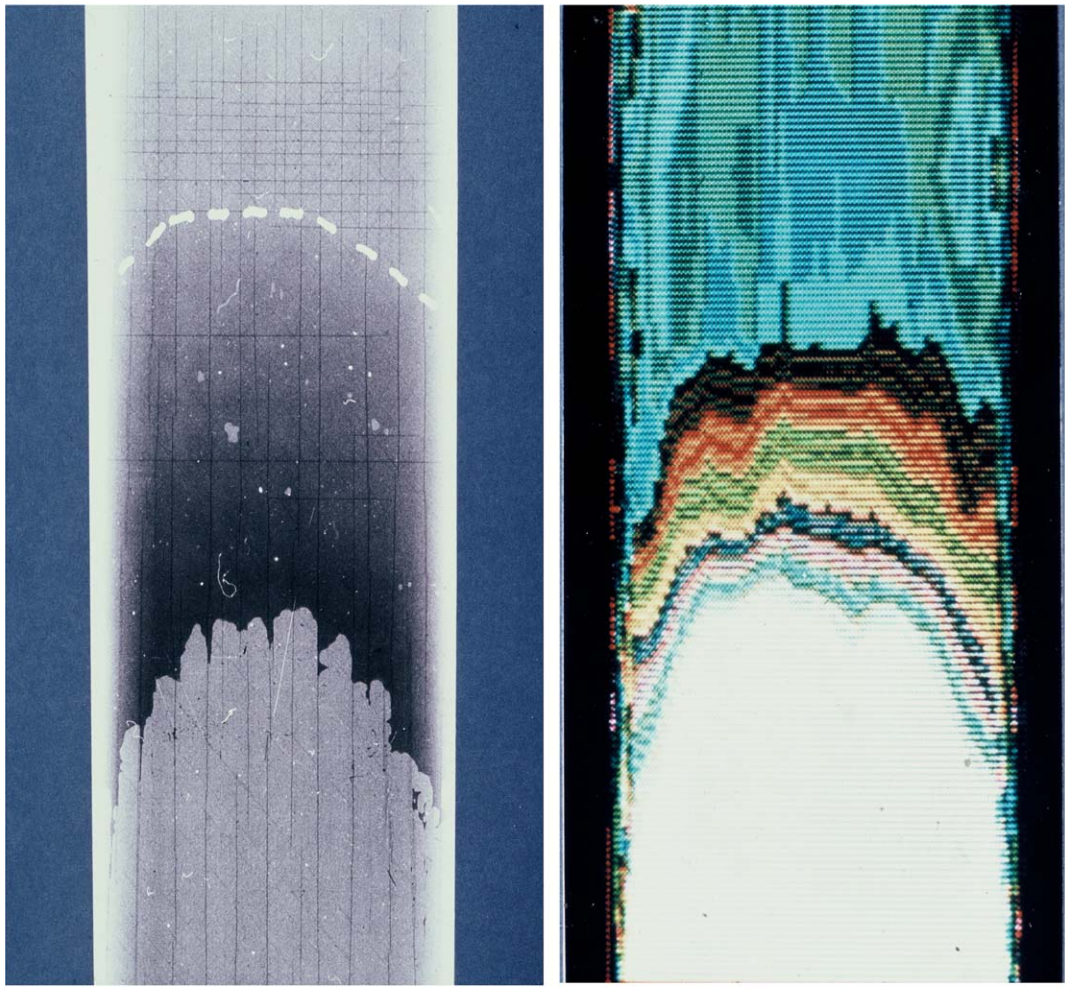
According the difference of fatigue mechanics, the fatigue laws are not the same. It is well known that the endurance curve of metallic alloys is quasi-hyperbolic in shape, with a pronounced concavity as soon as the maximum stress of the cycle exceeds the elastic limit of the material. The concavity of the endurance curve is attributed to the plasticity of metals. Below 10^5 cycle, when plasticity is generalized, the lifetime N_f is given (Fig. 2) by the Manson-Coffin relation:

$$\frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \alpha(2 \cdot N_f)^b + \beta(2 \cdot N_f)^c \tag{1}$$

in which ε_e and ε_p are the elastic and plastic strains. Considering that ε_p is negligible in high performance composites, the lifetime will be expressed by a relation of the form:

$$\frac{\Delta\varepsilon_e}{2} = \beta(2 \cdot N_f)^c \tag{2}$$

or



X Ray Radiography X ray Tomography

Fig. 1. Delamination damage zone in DCB specimens – quasi-isotropic T300/5208 laminate. Notice the microcracks in front of the tip of the delamination after fatigue.

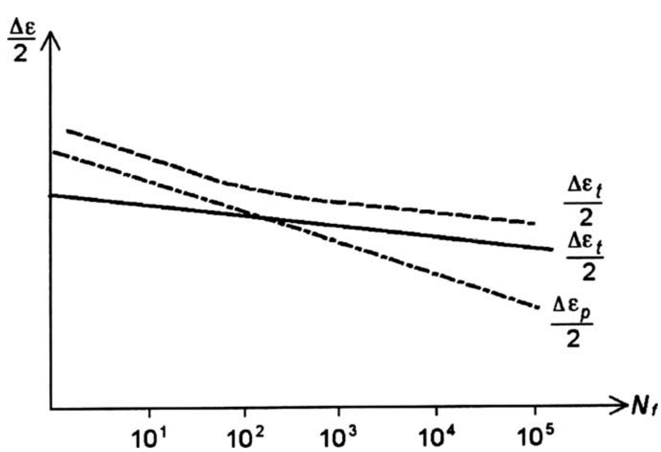


Fig. 2. Schematic low cycle fatigue curve versus applied strain.

$$\ln\left(\frac{\Delta\sigma}{2}\right) = \ln(\mathrm{b}) + \mathrm{c} \cdot \ln(\mathrm{N_f}) \tag{3}$$

Conversely, in composite materials, an appreciable alteration of the shape of the endurance curve can be reasonably expected. This low slope type of endurance has been roughly verified for high performance composite materials (Fig. 3). However, the very high cycle regime ($>10^7$ cycle) is unknown in composite materials since there is no drastic change between low cycle fatigue and high cycle fatigue behaviour, at the contrary of metals.

2.3. Effect of loading on the fatigue of composite

R ratio has not the same effect in composites than in metals. Under monotonic loading all composite materials present a compressive strength inferior to the ultimate tensile strength and decreasing as a function of the reinforcement: boron, carbon, glass, kevlar in that order. Under cyclic loading the behaviour is the same. At the limit, when the fatigue cycle is entirely in compression, fracture can occur (Fig. 4). This last type of damage is unknown in metallic alloys, which do not failed in fatigue in compression–compression [9,10]. For practical applications, it is extremely important to notice that in compression loading the ratio S_D/UTS can be as low as 0.3 for certain composites.

Fatigue in bending is another specific aspect of composite materials. A number of mechanical parts, such as

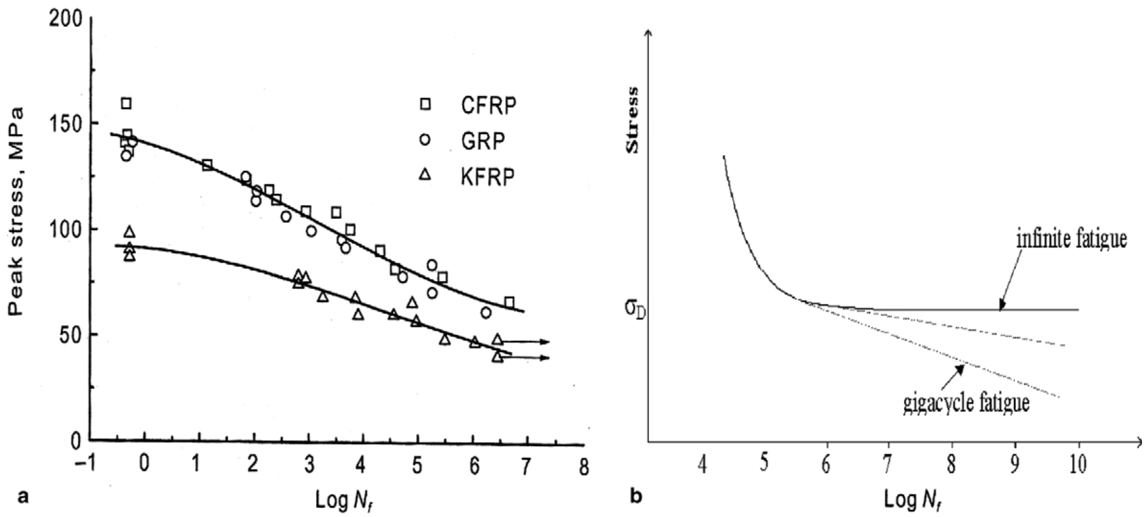


Fig. 3. Comparison of the *S–N* curve shape for composites and metals: (a). stress/loglife curves for composites materials tested at 45° to the main fibre directions: $R = 0.1$; $RH = 65\%$ [1]; and (b) stress/loglife curves for metals.

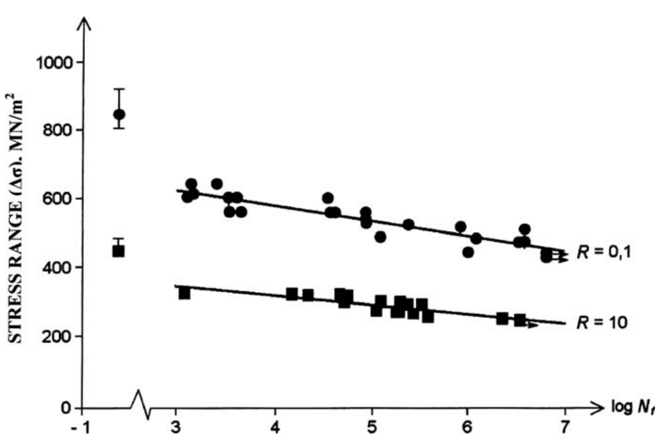


Fig. 4. *S–N* curves of $[0/\pm 30]_{3s}$ graphite/epoxy. Static strengths are shown at 1/4 cycle [10].

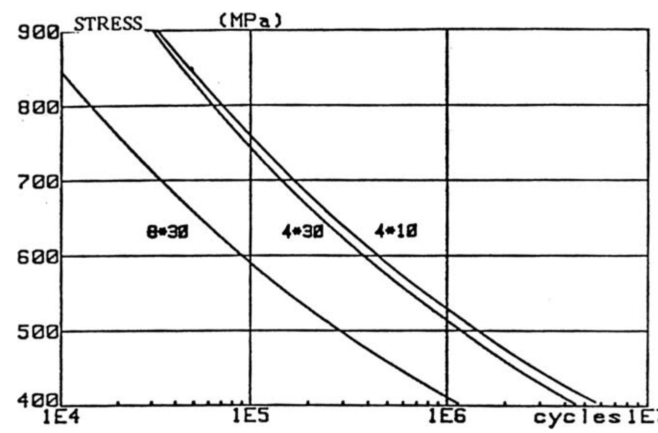


Fig. 5. Wöhler curves in three point bending at 5% of stiffness loss for 3 families of specimens with dimensions in mm (glass epoxy specimen).

springboards, are subjected to cyclic bending. The analysis of the phenomenon and of the results is complex, because several types of damage could occur in bending: tension, shear and compression simultaneously (Fig. 5). It is generally difficult to compare a result in bending fatigue with one in tension or compression. The behaviour in bending of composite materials is noticeably more difficult to determine than that of metals.

A small number of speculations deal with spectrum loading and damage accumulation in fatigue of composites. Nevertheless, the absence of plasticity and of the resulting residual stresses should explain that after tensile overload there is no retardation effect as it is for crack propagation in metals. It means that turbulences are beneficial for an aircraft component made in aluminium alloy but the same turbulence is detrimental for a composite material part (Fig. 6). Again, the damage accumulation prediction is different in composites and metals [11].

2.4. Stress concentration in fatigue

It is well known today that all metals are very notch sensitive and the so-called endurance limit then falls in significant proportions (Fig. 7). In composite, this phenomenon is practically unknown, which endows them with a definite advantage with respect to metals (Fig. 8). Comparing the notch effects of samples of 7000 aluminium alloy and of quasi-isotropic carbon fibre composite with K_t of 3.1, it is found that the stress concentration factor K_f in fatigue is less than 1 in composite and equal to 2.5 in the alloy for a lifetime N_f of 10^7 cycle [10].

On the other hand, if the ratio S_D/UTS is close to 1 in carbon fibre notched laminate loaded in tension–tension, this ratio is decreasing under 0.5 in compression–compression with $R = 10$ [12]. For the notched material, the endurance limit is between the UTS and the static residual strength where subjected to cyclic tension–tension (Fig. 9). If the load is compressive, the endurance limit is

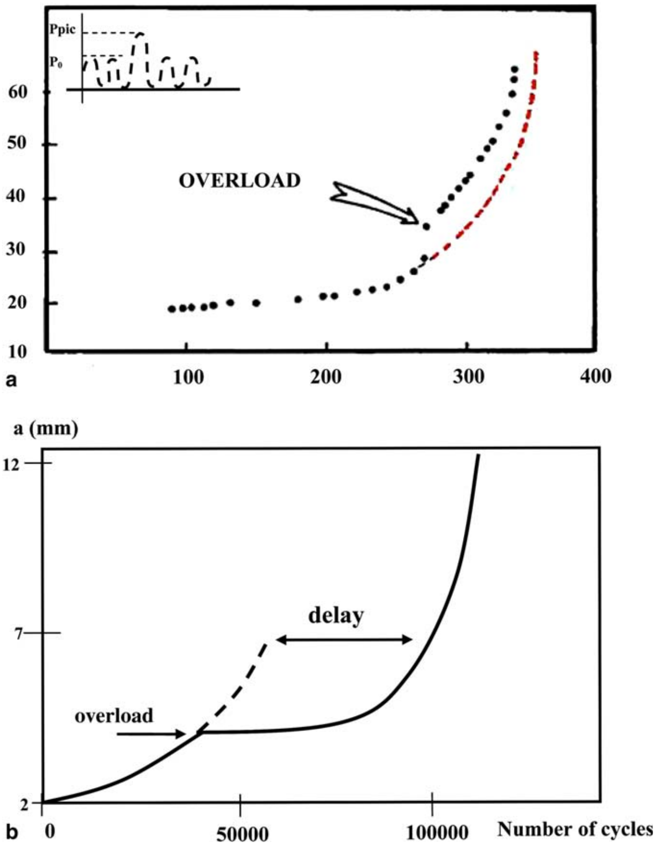


Fig. 6. Comparison of overload effect in composites and metals: (a) overload effect on delamination of glass fibre composite [11] with acceleration; and (b) overload effect with retardation of the fatigue crack in 2024 alloy.

clearly less than the residual compression strength. The process of damage in compression results from the formation of delamination in the external layers of composite which than propagate towards the interior until fracture [12].

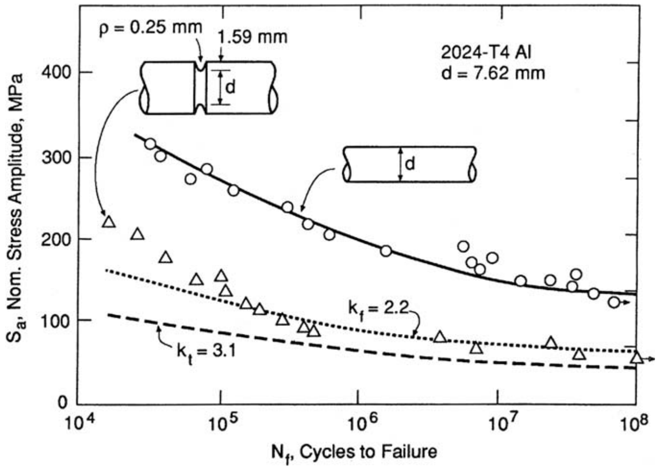


Fig. 7. Effect of a notch on the rotating bending *S–N* behaviour of an aluminium alloy, and comparisons with strength reductions using k_t and k_f.

2.5. Fatigue after impact

The fatigue of composite materials cannot be studied without taking into account the effect of the damage due to low energy impacts on the initiation of fatigue fracture. All things considered, the role of impacts in the fatigue of composites can be compared to that of machining grooved on the surface of metallic materials. In particular, the low energy shock provokes delaminations inside the composites, which can propagate under cyclic loading. This phenomenon is of concern because no surface damage appears on the impacted composite. Let us first recall that a low energy impacts on a quasi-isotropic carbon fibre composite plate leads to a decrease in UTS by approximately 30% and of compressive strength by 60% [13]. The fatigue limit in cyclic tension of the impacted materials is less than its UTS but especially notable is the fatigue limit in compression, which

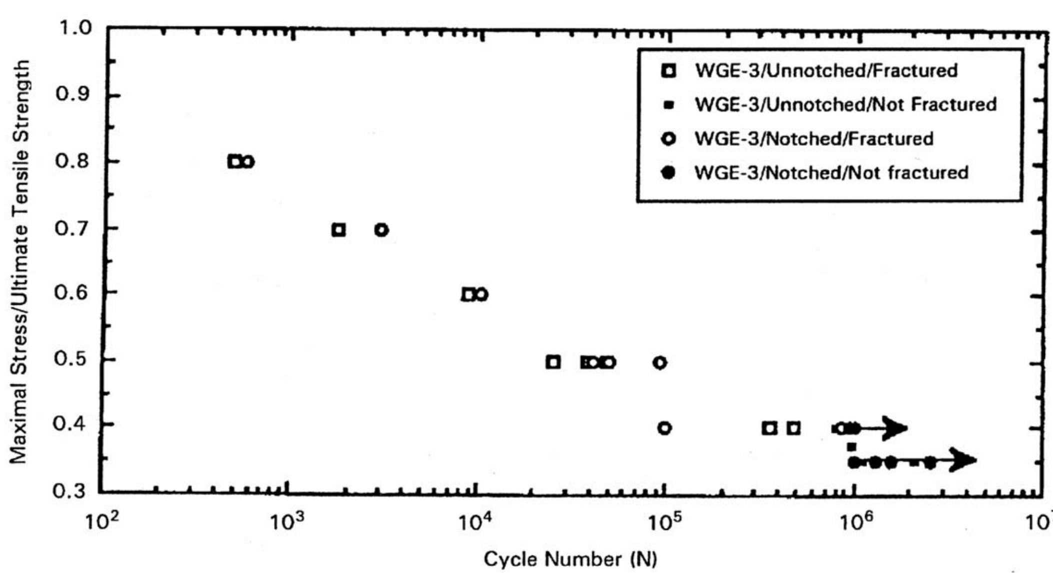


Fig. 8. Effect of a notch on the fatigue life laminate glass fibre composite [12].

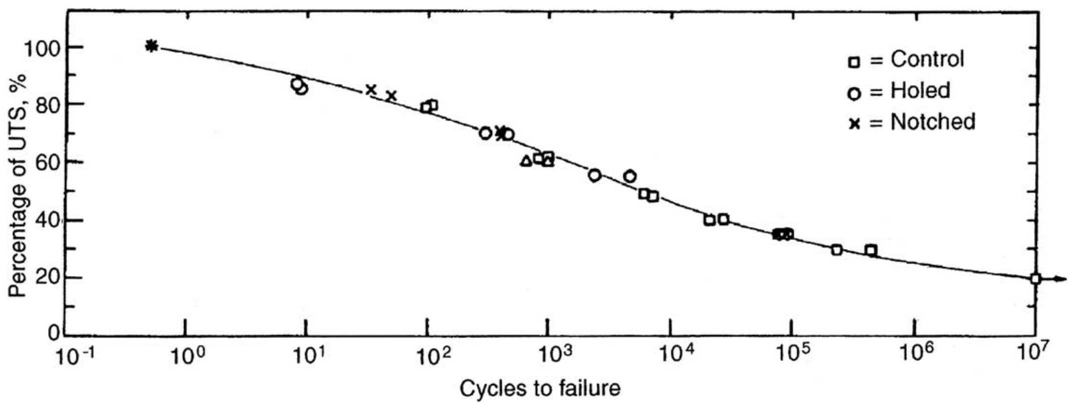


Fig. 9. Normalized fatigue data for double-edge notched, centre holed and control glass-fibre fabric epoxy specimens [1].

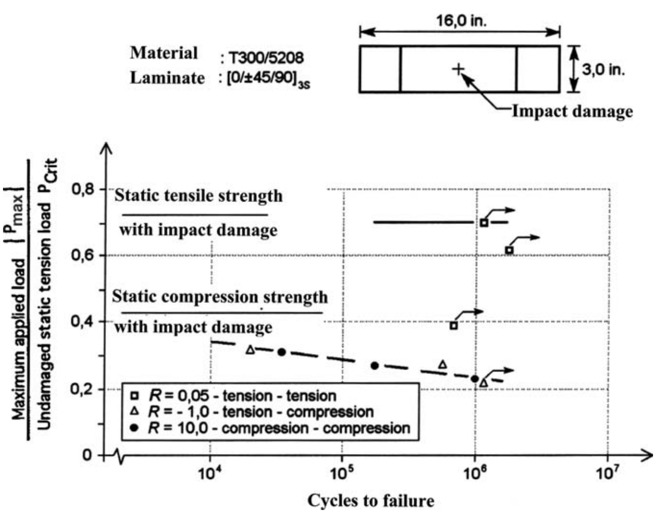


Fig. 10. Influence of stress ration on fatigue life of laminate with impact damage [13].

drops to 20% of the nominal UTS of the undamaged material (Fig. 10).

The damage provoked by a light impact is thus to be taken into consideration in the prediction of fatigue fracture, in the form of a correction for a tensile load and as the principal parameter for a compressive load ($R = -1$ or $R = 10$). It is emphasized again that compression loading of composites is detrimental.

3. Conclusion

The fatigue of high performance polymer matrix composite materials differs in several aspects from that of metallic materials, as follow:

1. The specific endurance strength of composite materials subjected to cyclic tensile loading is generally greater than that of metals.
2. Composite materials are less sensitive in fatigue to the notch effect than metals.
3. Cyclic compressive loads lead to important damage of composites.
4. Impact damage is a key factor to predict fatigue endurance especially in compression.
5. The giga cycle fatigue of composites is unknown compared to metals. Damage due to heat generation is not understood.
6. The specificity of the fatigue of composites depends on the damage mechanics such as transverse cracks, delamination, debonding, edge effects, thickness and staking sequence [1,6].

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