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Uniaxial Ratcheting of Fiber Glass Reinforced Epoxy: The effect of the fiber orientation

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***Abstract*- A series of finite element analysis have been undertaken on Fiber Glass Reinforced Epoxy (FRGE) laminates having fiber orientation of ± 30º, ± 45º and ± 60º subject to axial. Ratcheting of the FRGE laminate has been observed and recorded in the axial direction using ABAQUS package. The results obtained from the finite element work shows a direction in fiber orientation seemed to have effect on the rate of ratcheting. The composite with fiber orientation angle ±60° from the axial load had shown the highest rate of ratcheting compared to fiber orientation angles ±45° and ±30°. Thus, the increasing of fiber angle from the axial load will increase the rate of ratcheting.**

I. INTRODUCTION

Cyclic ratcheting, which occurs under asymmetric cyclic stress, refers to progressive accumulation of plastic strain as the number of cycles increases. The ratcheting deformation accumulates incrementally with the applied number of cycles, and it may not cease until fracture. The ratcheting contributes to the material damage, and thus results in reduced fatigue life. Ratcheting has been observed in many engineering components. Welded nozzles of pressure vessels, pipelines, and micro-electromechanical systems are among these components. Cyclic ratcheting of rolling stock due to high compressive stresses that are superimposed on cyclic shear produced by friction at the wheel/rail contact is another example. In such cases the long-term effect of ratcheting is of interest. [1]

However, it is often useful to examine the behavior of structures using simple material models in order to gain an understanding of the structure's behavior under specific loading conditions. This is particularly true when examining the possibility that a structure may ratchet [2].

There are numerous studies on ratcheting behavior. In the last two decades, uniaxial and biaxial ratcheting behaviors were studied experimentally and theoretically by some researchers, as reviewed by Ohno [3], Bari and Hassan [4], Abdel-Karim [5], Kulkarnia [6], Scavuzzo [7] and so on. The existing results showed that the ratcheting varies depending on the material type. The above-referred works were only focused on the ratcheting behavior and its constitutive model on metallic material.

However, researches on ratcheting behavior of composite materials are still relatively few. More investigations are necessary for in-depth understanding of the ratcheting phenomenon of this material. Material like Fiber Glass Reinforced Epoxy (FRGE) is typically used onshore and offshore for oil and gas industry. Thus, the simulation has been performed using the ABAQUS software package for this material to understand their behavior under uniaxial loading conditions.

The fiber orientation of the composite material is the important characteristic on the structure properties. The elastic modulus is much higher when a stress is applied in the direction of fiber orientation than when it is applied transverse to it. Therefore, a parametric study was carried out in this present paper to determine the effect of fiber direction to ratcheting rate of FRGE laminate. The combination of fiber orientations were investigated here is commonly use in composite pipes. This parametric study was performed using finite element model in ABAQUS program.

II. MATERIAL MODEL

There are many combinations of fiber orientation in fiberglass reinforced epoxy pipes were manufactured. In this study, there are three combinations of fiber orientation were selected where ± 30º, ± 45º and ± 60º subject to axial. Fig. 1 shows the fiber orientations of composite were selected.

Multidirectional fiberglass laminates were reinforced with epoxy in a square configuration. The principal directions of the fiber arrangement were aligned with the specimen axes, as defined in Fig. 1. The specimen were cut from the composite plates with a diamond-grit saw and ground to a width of 25mm. Thickness of the laminates was 1.5 mm. Aluminium tabs of length 50mm and thickness 2 mm were adhered to the specimens using Hexcel Redux 322 heat-cured epoxy sheet leaving a 100mm gauge length. The recommended cure cycle was used one hour at 180°C under pressure, with suitable heating and cooling rates.

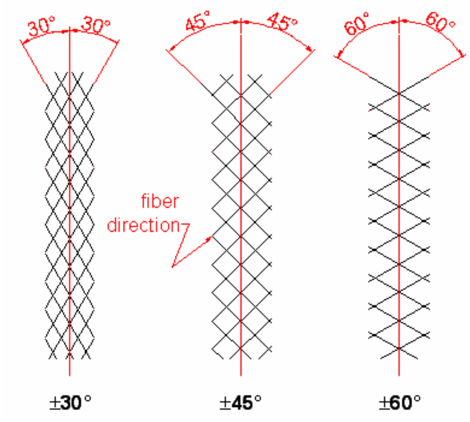
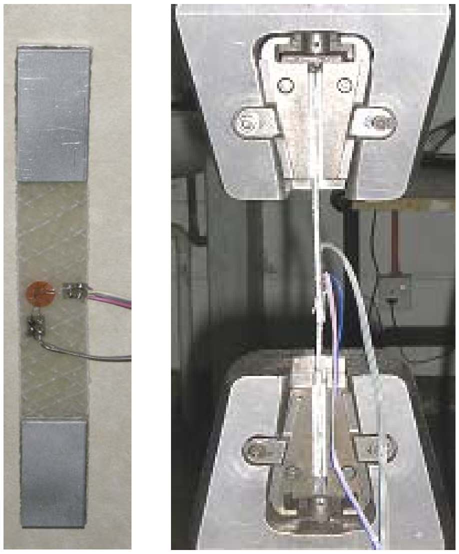


Fig. 1: Fiber orientation of composite.

(c) Experiment setup

Fig. 2: Setup of the monotonic tensile test.[8]

Since the specimen will be modeled as an isotropic material in ABAQUS, the monotonic tensile test was conducted first in order to obtain the stress-strain curve characteristic of the specimens, as an input program. The results are important in order to predict the value of loads and material model in ABAQUS package. The specimen with the fiber orientation angle is ±30° (Fig. 2(a)) is installed with the strain gauge in the axial and transverse direction as shown in Fig. 2(b). The specimen was loaded to failure, and both the load and axial strain were logged at a sampling rate of 1Hz. The test was repeated for laminate with fiber orientation angle ±45° and ±60°. As a result, the monotonic stress-strain curve in axial direction for each specimen is given in Fig. 3, Fig. 4 and Fig. 5.



(a) Specimen (b) Installed with strain gauges

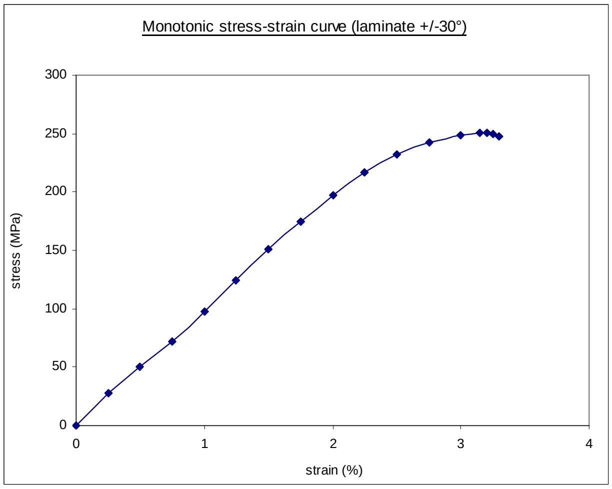


Fig. 3: Monotonic tensile test curve for laminate ± 30º fiber angle.

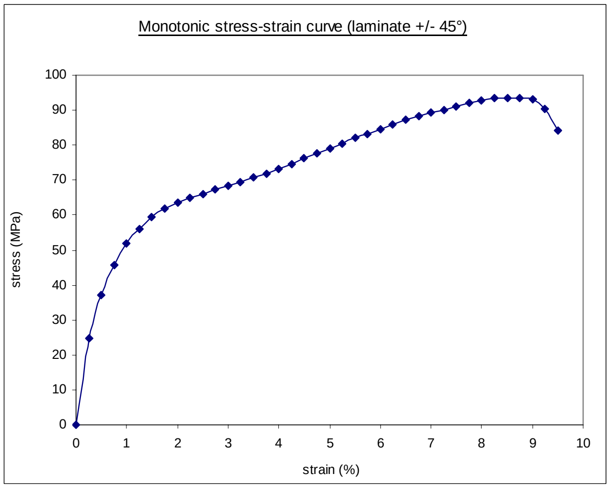


Fig. 4: Monotonic tensile test curve for laminate ± 45º fiber angle.

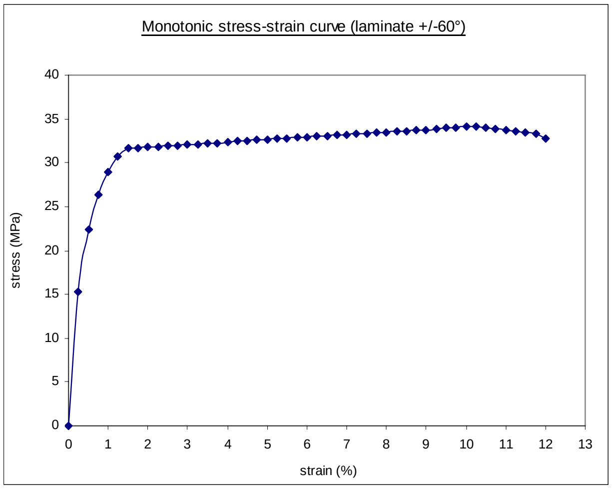


Fig. 5: Monotonic tensile test curve for laminate ± 60º fiber angle.

III. Uniaxial Rachetting Rate

In this parametric study, the uniaxial ratcheting rate was investigated in order to determine the effect of fiber orientation in composite laminate. In the uniaxial ratcheting test, the controlled variable was axial load (which implied controlling the stress of the specimen). Since the strength for each specimen is different, the axial cyclic load which was applied is based on their yield stress. The specimens were subjected to cyclic loading with $\sigma_m \pm \sigma_a$, where σ_m is mean stress and σ_a is stress amplitude. The mean stress was set is equal to the yield stress (which was obtained in the monotonic tensile test) and the stress amplitude was set as 0.33 of yield stress. The load application for this test in ABAQUS program was summarized in Table I.

TABLE I
LOAD FOR UNIAXIAL RATCHETTING TEST

Laminate (fiber orientation)	Mean stress, ($\sigma_m = \sigma_y$) (MPa)	Stress amplitude, ($\sigma_a = 0.33\sigma_y$) (MPa)	Max Load (N)	Min Load (N)
± 30º	198	± 65.3	9,875	4,975
± 45º	40	± 13.3	2,000	1,000
± 60º	20	± 6.6	1,000	505

Fig. 5 shows the finite element model of the specimen. The model was loaded for 8 cycles.

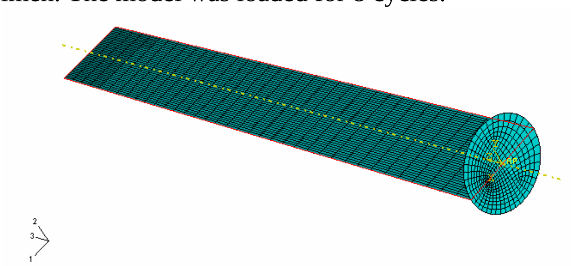


Fig. 5: Finite element model of the specimen.

IV. Results and Dicussion

Table II shows the results of uniaxial ratcheting rate for each models, laminate with fiber orientation angle ±30°, ±45° and ±60°.

TABLE II
RATCHETING RATE OF UNIAXIAL TEST RESULT

Fiber angle / Cycle	± 30º (μ)	± 45º (μ)	± 60º (μ)
1	326	726	1617
2	199	501	1260
3	174	426	1041
4	120	325	878
5	117	301	774
6	111	276	689
7	85	229	620

Fig. 6 shows the effect of fiber orientation to uniaxial ratcheting rate of composite laminate. According to the figure, it is shown clearly that the laminate with fiber orientation ±60° to the axial load produce the highest rate of ratcheting compared to the fiber orientation ±45° and ±30°. In a steady state condition which at the last three cycles, fiber orientation with ±60° produce the ratcheting rate 694 μ, while fiber orientation ±45° and ±30° produce 269 μ and 104 μ. Hence, it can be concluded that the increasing of fiber angle from the axial load direction will affect the increasing rate of ratcheting of the composite structure. However, the rate of ratcheting for all models was initially high and stabilize reduced in subsequent cycles.

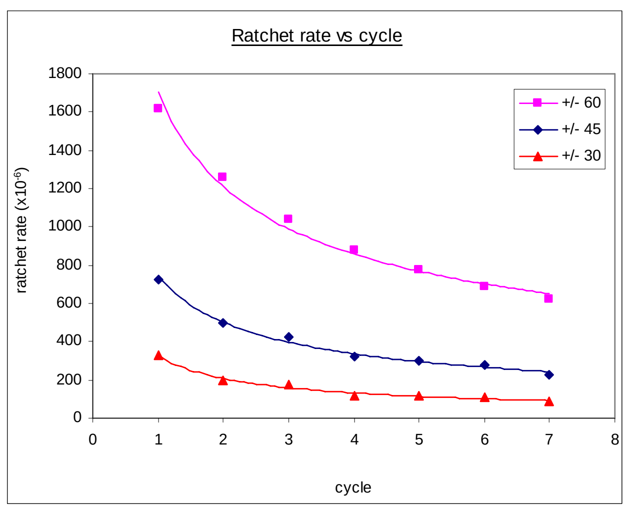


Fig. 6: Effect of fiber orientation to ratcheting rate.

It should be noted that only uniaxial ratcheting is discussed in this work. In the other hand, the above-mentioned results are all empirical and cannot be directly used to predict the ratcheting failure in the designing of structure components [3]. To achieve the preventing of ratcheting failure in structure components, some models that can predict the cyclic deformation and failure of practical components under various loading types should be established in terms of the corresponding experimental results shown above and implemented into finite element method.

V. CONCLUSION

A series of finite element analysis has been conducted on Fiber Glass Reinforced Epoxy (FRGE) laminates having fiber orientation of ± 30º, ± 45º and ± 60º subject to axial. In the tests reported here, a direction in fiber orientation seemed to have effect on the rate of ratcheting. The composite with fiber orientation angle ±60° from the axial load had shown the highest rate of ratcheting compared to fiber orientation angles ±45° and ±30°. Thus, the increasing of fiber angle from the axial load will increase the rate of ratcheting.

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