CYCLIC LOAD AND RESIDUAL FLEXURE STRENGTH OF PLAIN WEAVE CARBON/EPOXY COMPOSITE – AN EXPERIMENTAL VERIFICATION

Engineering

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ABSTRACT

The growing use of plane-weave carbon fiber reinforced composite in aerospace components design demanded to support and define the engineering concepts of durability and damage tolerance. After fatigue damage, the reliability information in terms of flexure strength investigated in this paper. A series of three point flexure tests conducted over the range of cyclic damaged specimens. The experimental results analyzed with reference to residue strength and reduced stiffness of the CFRC specimens. Fatigue damage followed by flexure tests produced significant strength reduction in comparison to simple flexure tests, and the reduction in residual flexural strengths and stiffness purelydepended on the magnitude of fatigue stress applied with number of cycles subjected to bi-directional woven carbon/epoxy composite specimens.

KEYWORDS

Woven CFRC, Cyclic Damage, Flexure Test, Residual Strength, Residual Stiffness

Introduction:

Structural components made of carbon fiber reinforced composite shown significant potential in wide variety of structural applications such as in aircraft and aerospace industry, automobile industry, sporting goods, offshore structures, and civil engineering[1]. This composite material possess attractive properties like, the high strength to weight ratio and high stiffness to weight ratio, excellent fatigue strength, ease of formability, wide range of operating temperatures (thermoplastic resins and carbon-carbon composites), negative or low coefficient of thermal expansion, high damping, resistance to corrosion, and flexibility for being tailored according to requirements[2,4,6]. Instead of all these virtues, the safety, reliability and durability of this material are directly depends on material responses under a number of controlled conditions or what is more commonly called as fatigue and post-fatigue behavior andcan avoid the unseen challenges of this composite material[3,5,7,8]. For example, the relationship between damage modes, failures modes and the state of microstructure of composites define the manner in which composite could be designed for a long-term service and under external influences such as mechanical, thermal, chemical and catastrophic loading. Also, thechanges shall be correlated on the line of certain rational approach, so that fundamental questions like safe life of the component will be determined in fairly general circumstances[2]. In concise, it is desired to predict the residual strength and stiffness as a function of material life and loss of mechanical strength of this newly immerged material, before using it in full scale.

Understanding, fatigue degradation of material is critical to ensure the long-term reliability of a components and structures. The evaluation of residual strength of in-service parts is important to ensurestructural integrity (catastrophic failure does notoccur). The residual strength and stiffness test allowsthe evaluation of remaining strength and stiffness in astructure after a given life cycle.Reviews of previous researches revealed that the fatigue failure could be defined in terms of material strength $(_{\sqcup})$, material stiffness and material modulus[1-31]. As the fatigue cycle increased with constant loading, the fatigue life also reduced sizably. It is required to investigate the percentage of degradation of material strength with respect to fatigue stress and dynamic cycles. There is several method of observation and modeling the degradation, and it is quite complex in case of composite. As composites have flexibility to tailor made into required orientation, and lamination, so complexity of various failure mode varies on different types of fabrication, material inclusion and method of fabrication. Research related to monitoring the residual strength degradation through experimentation, modelling, and statistically scaling of fatigue damage and successive effect over the material reported earlier under different loading environment[1]. Also, the research related to environmental effect on fatigue of composites and strength degradation are well documented before. Poursartip et al (1986)reported the damage mechanism ofcarbon fiber composite both experimentally and theoretically. The residual strength ofmultidirectional carbon fiber laminated composite has been

investigated by Rotem (1988). Beamount (1990)studied the static and cyclic loading impact and the effect of environment on accumulation ofdamage in composite laminates. Eggers et al (1991) studied the characteristic damage state in cross plylaminates of carbon fiber reinforced epoxy under varied stacking sequence, tensile fatigueloading and thermal cycling. The prediction of fatigue life and evaluation of fatigue damage forcomposite laminates has been investigated by Liu and Lessard (1994). The remaining strength and life ofcomposite materials with time and cycle dependent degradation process has been analysed byReifsnider and Xu (1995). Kawai et al (1996) studied the influence of matrix durability on progressive damageduring fatigue loading on carbon fiber plain woven roving fabric laminate. Hwang and Han(1989) presented a theoretical modeling on fatigue damage and life prediction of composite. Agrawaland Joneja (1982) studied strain controlled flexural fatigue of unidirectional oriented reinforced glassfiber epoxy composite. Ozaki et al. (2015) reported the residual flexural strength after impact damage of textile made carbon fiber reinforced composite. Imet al. (1998)studied the static and fatigue bending strengths of CFRP laminates having impact damages via foreign object.

In this paper, the residual flexural strength and stiffness of woven carbon fiber reinforced compositewith constant volume fraction and constant thickness has been determined after different cyclesfatigue damage at various stress cycles. The observed results are presented in form of cumulative damagedegradation rate.

Experimental procedure:

i) Materials and specimens: A plane-weave carbon fiber cloth with epoxy resin used as materials for the current test program. The fibers INDCARF–30 type with 3K-filament count, a product of IPCL, and a non-hygroscopic epoxy resin matrix (Araldite – LY5052 and a hardener – Hy5052), a Ciba-Geigy product were used for specimens fabrication. The laminates were laid-up as a 8-ply in the form of ( )8and were autoclave processed using a classical 180^{0}C epoxy cure cycle. The so-cured laminates were about 1.68mm thick, and had a nominal 55% fiber volume fraction. After fabrication, the laminated plates were scanned using an ultrasonic probe immersed in water to assess their quality and to determine areas of potential weakness.

A microphotograph of specimen's cross section with fiber distribution is shown in photograph (a). The laminates were then cut using a diamond-tipped slitting wheel into individual specimens measuring (fig.1) 90X 25X 1.68mm (ASTM STD D790) for three point flexure testing and 90X 30X 1.68mm for fatigue testing as specified for the machine (fig. 2).

ii) Flexure testing: Three point bending flexure tests were carried out under a UTM and as per ASTM D 790M standard. The dimension of ASTM specimen is shown in fig. 1. A pair of dial gauge is used to monitor the deflection at the bending point. The flexure modulus has been determined from the slope of load vs. deflection diagram, and

presented in Table-1.

iii) Fatigue testing: The fatigue tests were carried out in a rotary bending fatigue testing machine with complete reversal cycles and at a frequency of 24Hz to determine the fatigue strength (S) and number of cycles (N). The detailed dimension of fatigue specimen is shown in fig. 2. A 30N-m dynamometer has been used to provide the cyclic deflection.An eccentricity equal to R= -1were maintained during the fatigue test. S-N diagram is shown in fig.3 from obtained data to scale the fatigue strength of the CFRP specimens.

iv) Fatigue-Flexure Test: Residual flexure strengths were measured after performing the fixed fatigue cycles at pre-selected fatigue stress on the fatigue specimen (fig. 2). Three different cyclic stresses like 309MPa (58% of UTS), 234MPa (40% of UTS), and 160MPa (28% of UTS) were applied for a range of fatigue cycles, i.e. 10^3, 10^4, 10^5, and 10^6cycles for growth of fatigue damage.

Then, three point flexure tests were carried out over these fatigue damaged specimens to determine the residual flexure strength. The deflections gauges were used similar to flexure testing and residual flexural modulus were determined from load vs. deflection curves. The results are shown in Table 2 and 3.

Results and Discussion:
Experimental observations are analyzed on the following paragraph quoting suitable tables, photographs and figures.

i) Flexure strength:
The flexure strength found out through three point bending flexure tests for standard ASTM specimens (fig.1.a) and for fatigue specimen (fig.1.b)had shown 7% variation in their results (Table-1). Likewise, the flexure modulus determined from load deflection curve during the three point bending tests had shown 11% variation when compared. The average results of six specimen's flexure strength and flexure modulus are presented in table-2.

As the failure of a flexure loaded composite specimen depends on the type of fiberalignment to load and thickness of the specimen, the flexure load transferred to the horizontalaligned fibers produced moment and failed in any of the mode, i.e., tension, compression, orshear. Also, the combination of these modes has been resulted in certain cases. Failure isinitiated, when any of these three stresses has reached its corresponding limit. If flexure stress isequal to shear stress, then flexure strength is same as inter laminar shear strength, and again ifflexure stress is greater than longitudinal tensile or compressive strength, one of the highlystressed outer plies has failed due to matrix deformation. Horizontal shear failure in terms ofsplitting has the main feature in majority specimens as found in present study. Also, thewrinkling of the compression surface near the load nose and permanent shear deformation ismarked. Including to above causes, another difference for fatigue specimen is that it has less areaat flexure loading point, and hasreduced strength due to stress concentration effect.

ii) Fatigue strength:
Rotational bending fatigue tests at different bending moment were carried out todetermine fatigue life of carbon fiber reinforced composite specimens and shown in fig. 3 in form of S-N graph. Thefatigue lives of the tested specimens were distributed in between 70% to 55% of tensile strengthand at the cyclic range of $10^3$to 10^7cycles. The photograph 'b', 'c' and 'd' have shown the type offailure of the specimens at different stress labels and at different number of cycles. As thecomposite have several modes of failure, like crazing, debonding, delamination, thermal residualstress effects, and crack propagation, it is possible to occur all in any combination in the fatigueprocess.

In addition, the peak stress was high enough to precipitate large numbers of fiber failureswithin the material at high fatigue stress and caused a progressive increase in matrix micro-crackswith stresses. The stress in the fibers was sufficiently within the fiber flaw strengthdistribution to produce a high fiber failure density. Failure then occurred by the coalescence oflocal fiber breaks which then propagated in a few cycles to content other such regions. Thespecimen failed catastrophically in a manner similar to tensile fracture. The first

half cyclesignificantly weakened the material often producing large cracks. The failure mechanism in thisregion was most properly described as combined static fiber fracture and fatigue.

As the stress value decreased, the number of reversal increased because the failureoccurred in following manner. First, micro cracks developed in the matrix because the stressexceeds the minimum micro crack initiation stress. Several random fiber breaks were alsoobserved, but not in the larger numbers that led to incipient failure. Instead, the fiber breakswithin the material appeared to play a small role in fatigue behavior in this region. As cyclingprogressed, one (or more) of the surface micro cracks were seen to propagate perpendicular tothe tensile axis (photograph 'c'), breaking fibers in its path until it was large enough to satisfy the criterion forshearing type propagation parallel to the fibers. When this occurred, delamination began, leadingto a loss in the apparent modulus and eventual failure.

At above than 10^6cycles, the maximum plied stress was close to the micro crackinitiation stress. A few fiber failureis were observed (photograph 'd'). But these did not increase with subsequentcycling. After a long operation of cyclic stress, some micro cracks were nucleated. This can bespeculated as the stress level is not sufficient for propagate a crack through the composite. Thestress corrosion mechanism requires a minimum stress below which the crack tip radius does notincrease and resulted in little further crack growth.

The above discussion can be observed frommicrophotograph. The photograph 'a' is a cross sectional view of specimen with fiberdistribution. The photograph 'b' is standing for high fatigue stress with single crackdevelopment, which propagated to failure. The photograph 'c' is illustrating the crackpropagation similar like shear failure. The photograph 'd' is signifying the failure mode withinclusion of multimode crack developments.

iii)Residual Flexure Test:
The residual flexural strength determination through three points bending over variousfatigues damaged specimens revealed the series of strength and stiffness variation at different fatigue loading as shown in fig 4 to 13. In high fatigue stress, it has been observed that the flexure strength reduced to 69% of real flexure strength at 10^3cycles and ended at 36% at 10^6cycles (Fig. 4).Similarly, the residual flexure strength remains 77% at 10^3cycles and reduced to 50% after 10^6cycles at cyclic stress 234MPa (fig. 5) and 79% at 10^3cycles and reduced to only 59% aftercyclic stress of 160MPa (fig. 6).

From above results it has been found that there is sizable reduction in flexure strengthdue to cyclic load application and shown in terms of percentage flexural strength reduction in fig.4, 5, 6, 10, 11, 12, and 13. The damage occurred due to cyclic stresses are being considered asthe function of micro damage events, continuity on damage process, and finally macro damageevents on the specimens. The micro damage events is attributed to early fatigue cycles whichdeveloped matrix cracking, fiber braking, fiber pull out, and debonding. These micro damageevents are further aggravated when cyclic stresses continuously applied on the damage boundary.The nucleation and propagation of micro cracks coalesced to form multiple crack fronts, andmagnified at increased number of stress cycles as shown in photograph'd'. These crack frontsadvances with continuous manner. Then, the micro event is changed a macro size by furtherincrease of stress cycles. All these events are depended on size of cyclic stress, number of cycles,and the specimen type, and are well marked through resulted data (table 2) and plotted figures 4-13.

When a fluctuating load is exerted on specimen, the specimen responded by deformingaccording to its stiffness. As the load was sinusoidal and constant in amplitude, the deformationis also sinusoidal as expected, but the amplitude is changed with time and thus stiffness. Thiscould be correlated as *Stiffness (cycles)* = $\frac{Load}{Deformation}$ Thus, stiffness changes are depended on the change of the apparent modulus (Table-3).The modulus related to matrix is most affected by the fatigue process. In a single laminae, themodulus of fiber might be least affected. But, the specimen carried number of laminae and interlaminar properties are affected and simultaneously affected the stiffness. Delamination thatoccurred during the fatigue loading is one of the causes of reduction in apparent modulus oftested specimens.

In present observation, the material stiffness was found considerably reduced by fatiguestress. It has been observed that there is a reduction of stiffness round about 19% to 53% inbetween 10^3 cyclic ranges to 10^6 cyclic at 160MPa cyclic stress. This percentage was changed to 22% to 57% for 234MPa and 34% to 73% for 309MPa fatigue stress (Fig.7, 8, 9 and 13).

Fatigue behavior of composite laminate is dependent on the cyclic stress and the numberof cycles, which changes the local and global state of stress in the material. Damage eventswhich occur in progressive localized regions of a composite laminate cause change in load paththrough the material and also the load carrying ability of the material at the damage zone.The change in stiffness in composite specimen under long terms cyclic loading conditionis significant for two important reasons. First the limited deformation or stiffness of criticalelements which affects the stiffness adversely due to damage and secondly, the stiffness changesis directly related to severity of damage and subsequent response in the material.

Hence, the stiffness tensor changed in fatigue damaged specimen. As most of the loaddirection is fiber dominated, other engineering components like Poisson's ratio and shearmodulus are affected by matrix damage, and damage mode in off-axis ply in early fatigue life.The stiffness change occurred in three distinct steps. Step one, is characterized by an initial rapiddecrease of stiffness caused by matrix cracking and some early fiber break. Step two is anintermediate zone with stiffness reduction after long period which is resulted by matrix crackingin off-axis and on-axis plies crack coupling with angle ply and internal delamination. The stepthree is allied to rapid decrease in stiffness due to damage growth rate, delamination, coalescenceand fiber fracture. Consequently, the density of crack distribution increased in specimen andreduced the stiffness in sizable amount.

Conclusions:
Based on the experimental results, the following conclusions have been drawn. That,
1. The residual strength of the cyclic stressed bidirectional woven carbon/epoxy composite laminates produced significant stress reduction with respect to increased number of cycles and increased value of cyclic stress.
2. Also, a significant reduction in residual stiffnesshave been noted as the fatigue duration increased and sizably effected with respect to time interval of fatigue loading.

So, it can be very easily understood that if the damaged specimen run for higher number of cycles without care there is sever strength decrement and may cause the structural failure.
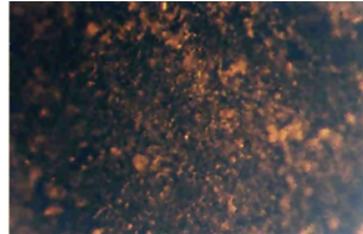
Table 1: Mechanical Properties of Woven Carbon/Epoxy Composite.

Specimen Composition	Volume Fraction (Vf)	Tensile Strength MPa	Tensile Modulus GPa	Flexure Strength MPa	Flexure Modulus GPa
INDCAF – 30 – 6K + Epoxy	55%	585ASTM 397 Fatigue	37.07ASTM 27.711 Fatigue	500 ASTM 463 Fatigue	30.64 ASTM 34.15 Fatigue

TABLE 2: Residual Flexural Strength of Woven Carbon/Epoxy Composite after Fatigue Damage at Different Fatigue Cyclic Stress

No. of Cycles	309N/mm²		234N/mm²		160N/mm²	
	Av. Residual Flexural Stress (N/mm²)	Variation from Original Strength	Av. Residual Flexural Stress (N/mm²)	Variation from Original Strength	Av. Residual Flexural Stress (N/mm²)	Variation from Original Strength
0	463	0	463	0	463	0
103	322.90	30.26%	384.59	16.94%	438.33	15.25%
104	281.41	39.22%	334.57	27.74%	428.32	21.75%
105	243.98	47.31%	289.23	37.53%	415.41	29.77%
106	178.23	61.51%	247.02	46.65%	404.57	36.52%

TABLE 3: Stiffness Values (Theoretical and Experimental) at Various Fatigues Cyclic Stress of Woven Carbon/Epoxy Composite

| Cyclic Stress N/mm²	No. of Cycles	Residual Stiffness E_R 10^3XN/mm²	E_R/E
160	10^3	27.658	0.81
	10^4	22.536	0.66
	10^5	19.463	0.57
	10^6	16.049	0.47
234	10^3	26.634	0.78
	10^4	22.501	0.61
	10^5	17.073	0.50
	10^6	14.683	0.43
309	10^3	22.536	0.66
	10^4	17.073	0.5
	10^5	12.975	0.38
	10^6	9.219	0.27

Photograph (a): Microphotograph of Cross sectional view of fiber distribution in woven carbon/ epoxy specimen

Photograph (b): Microphotograph of crack propagation during fatigue stress 400MPa.
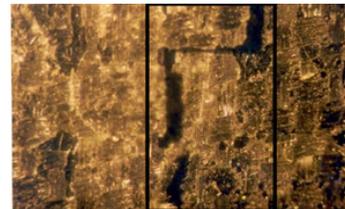
Photograph (c): Microphotograph of crack propagation in medium fatigue stress 350MPa
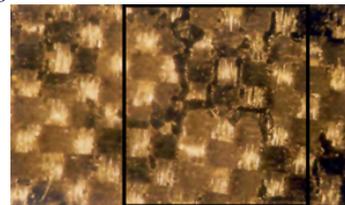
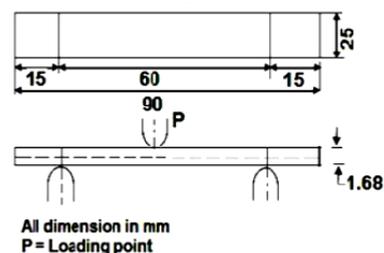**Photograph (d): Microphotograph of crack propagation in low fatigue stress 290MP**

All dimension in mm
P = Loading point

Fig. 1: Dimensions of flexure test specimens for 3-point bending method
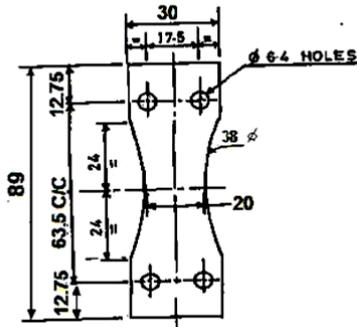
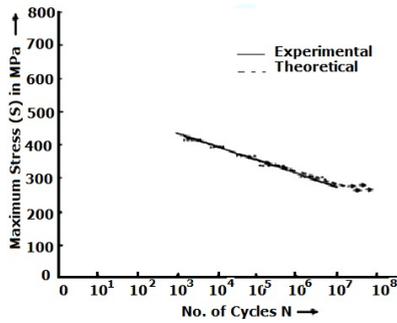**Fig. 2: Dimensions of Fatigue Test Specimens (All dimensions are in mm.)**

Fig. 3: S-N Diagram of bidirectional Woven Carbon/Epoxy Composite
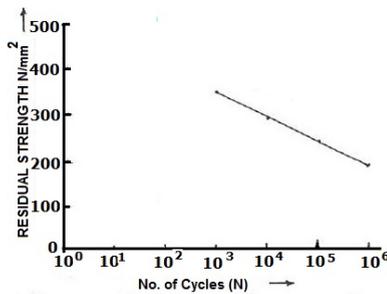

Fig. 4: Residual Flexural Strength at Different Cycles of Bidirectional Woven Carbon/Epoxy Composite after Cyclic Stress 309N/mm²
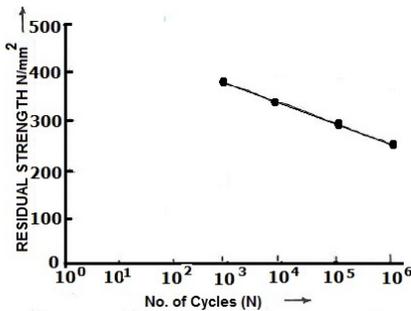

Fig. 5: Residual Flexural Strength at Different Cycles of Bidirectional Woven Carbon/Epoxy Composite after Cyclic Stress 234N/mm²
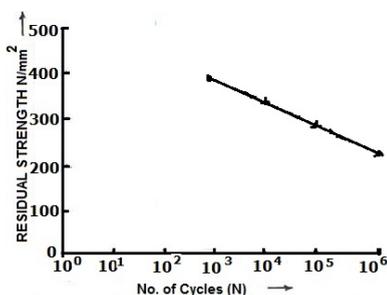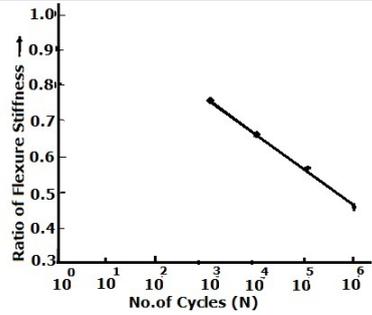

Fig. 6: Residual Flexural Strength at Different Cycles of Woven Carbon/Epoxy Composite after Cyclic Stress 160N/mm²

Fig.7: Ratio of Residual to Ultimate Flexural Stiffness of Bidirectional Woven Carbon/Epoxy Composite at Different Fatigue Cycles after Cyclic Stress 160 N/mm²
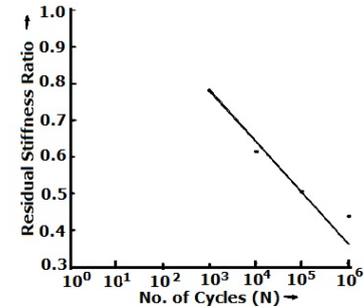

Fig. 8: Ratio of Residual to Ultimate Flexural Stiffness of Bidirectional Woven Carbon/Epoxy Composite at Different Fatigue Cycles with Cyclic Stress 234 N/mm²
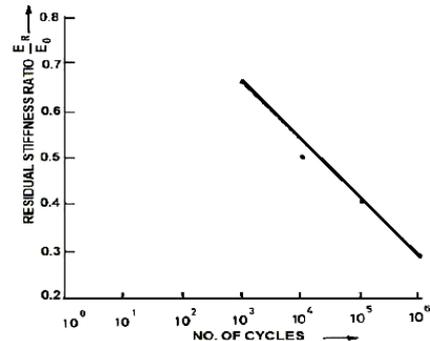

Fig. 9: Ratio of Residual to Ultimate Flexural Stiffness of Bidirectional WovenCarbon/Epoxy Composite at Different Fatigue Cycles with Cycle Stress 309N/mm²
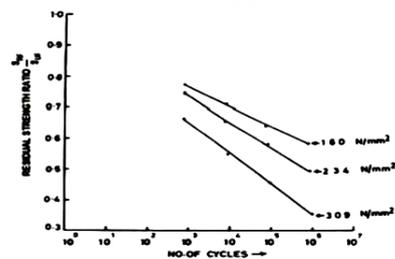

Fig. 10: Ratio of Residual Flexural Strength with Ultimate Flexural Strength of Bidirectional Woven Carbon/Epoxy Composite at Different Fatigue Cycles
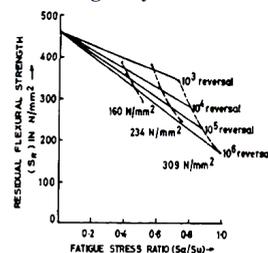

Fig. 11: Fatigue Stress ratio vs. Residual Flexural Stress at Different Fatigue Cycles
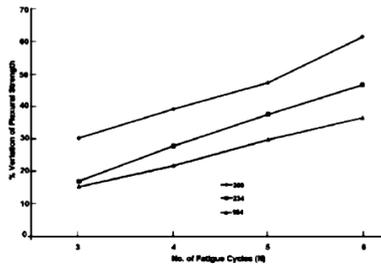
Fig. 12: Variation Percentage of Flexural Strength at Different Range of Cyclic Damage w.r.t. Original Flexural Strength
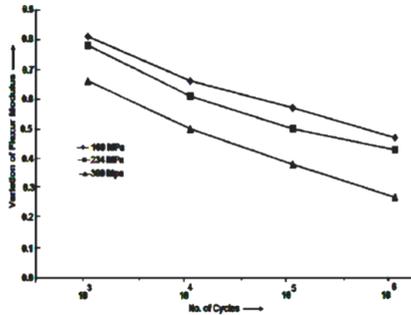

Fig. 13: Variation of Residual Flexure Stiffness with respect to Actual Flexure Stiffness at Different Fatigue Cycles

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