International Journal of Materials Engineering 2013, 3(4): 66-81
DOI: 10.5923/j.ijme.20130304.02

# Fatigue Behavior and Failure Mechanism of PU Foam Core E-glass Reinforced Vinyl Ester Sandwich Composites

**Manujesh B. J[1], Vijayalakshmi Rao[2,*]**

[1]Department of Mechanical Engineering, K.V.G. College of .Engineering, Sullia, D.K, 574327, Karnataka India
[2]Department of Materials Science, Mangalore University, Mangalagangothri, Mangalore, 574199, Karnataka India

**Abstract** The present work is concerned with the study of flexural and fatigue behavior of E-glass fibre/Vinyl ester/Polyurethane foam sandwich composites. Four types of sandwich composites are prepared with polyurethane foam and E-glass fabric/ vinyl ester facesheet having glass: vinyl ester weight percent ratio 65:35 by hand lay-up method followed by compression technique at room temperature. The specimens are then tested for flexural/fatigue behavior. The objective of the present work is to investigate the integrity of facesheet with core under fatigue on varying the density of PU foam and by changing the fibre architecture. The fatigue behavior is observed for frequencies 1Hz, 3 Hz, 5 Hz, 7 Hz and 9 Hz. The experimental study reveals that the cyclic load and test frequency play a critical role in determining fatigue strength. The fatigue strength increased with increase in density of PU foam. Stiffness degradation increased with increase in the fatigue frequency. The failure modes observed are facesheet/core debonding, delamination and core shear failure.

**Keywords** Fatigue Behavior, Sandwich Composites, Stiffness Degradation, Debonding, Delamination

## 1. Introduction

A sandwich structure consists of two thin, stiff facesheets bonded to thick lightweight and weaker core material. The face sheets carry most of the bending and inplane loads while the core provides structural stiffness, and out of plane shear and compressive strength[1]. Properties like high stiffness and specific strength has been exploited in application of sandwich composites as structural materials[2]. The increasing use of sandwich composites in a lot of engineering applications has motivated researchers to investigate their properties. During the regular service, sandwich composites are subjected to dynamic loads that may cause some induced stresses in the structures[3]. Many applications like aircraft structures, marine vessels, car body parts and train & truck structures involve cyclic loading, which can degrade the mechanical properties of the composites and generate fatigue failure. Therefore their fatigue behavior is significant in reliability and ensuring safety of these sandwich structures. Hence an understanding of fatigue behavior is important prior to its use in these applications. Fatigue damage can be evaluated from the stiffness, residual strength or other mechanical properties. Stiffness degradation occurs during the fatigue life. The flexural fatigue strength of sandwich structure depends on the strengths of outer facesheet, foam and interfacial bond strength between the facesheet and the light weight core. The failure of any one of these would cause failure of the sandwich structures[4, 5].

Fatigue behavior of foam materials like PVC, PU, PMI, polycarbonate foam materials used as core in sandwich structures have been reported by many researchers[6]. Studies carried out by Zenkert and Backlund[7] includes static tests to investigate the rigidity and stiffness of PVC foams. These studies showed that linear elastic fracture mechanics can be used to estimate the failure of PVC foams. Lilley et al.[8] investigated fatigue crack growth in polyurethane foam using fracture mechanics parameters and have shown that using fracture mechanics approach it is possible to rationalize the crack growth and assess the effect of R-ratio[8]. Similar work has also been executed by Yau and Mayer[9] on polycarbonate foam under fatigue loading. Zenkert[10] has investigated the fatigue properties and the physical behavior of fatigue damage in PVC foam materials. Grenestedt has described crack propagation in PVC foams [11]. Shipsha et al. have studied mode-I and mode-II modes of failure by crack propagation in PVC foams[12].

Several reports are available on the fatigue behavior of foam core sandwich structures[13-18]. A thorough investigation on the fatigue crack formation and growth has been made by Burmen & Zenkert[13] on two different

* Corresponding author:
vijrao@yahoo.com (Vijayalakshmi Rao)
Published online at http://journal.sapub.org/ijme

sandwich configurations; with PVC & PMI foam cores and epoxy/glass facesheets. Damage initiated in the zone of high shear stresses over the entire length of the zone and in the middle of the specimen. These micro damages grew together and formed a horizontal macro crack whose length depended on the size of the shear zone coupled to the length between the load supports. Once the macro crack had developed, the two crack fronts kinked away and grew towards the face/core interfaces in directions corresponding to maximum tangential stress. The effects of interfacial crack size and impact damage size on the shear properties and failure mechanisms of marine sandwich composite made of glass reinforced polymer (GRP) skins and a polyvinyl chloride (PVC) foam core was reported by P S Thomas et al.[17]. An abrupt decrease in the static shear strength and fatigue resistance occurred when the interfacial crack length between the skin and core exceeded ~20-30 mm due to the failure mechanism changing from wrinkling of the GRP skin to shear cracking of the foam core. The fatigue performance was reduced with increasing interfacial crack size, although the load capacity of the composite remained unchanged until complete failure of the core. The fatigue failure of the core is characterized by a crack initiation stage and a steady-state crack growth stage, with each stage having a different crack growth rate[17]. The fatigue characteristics of polyurethane foam cored (PUF) composite sandwich structures were investigated using three-point bending tests[18]. Three types of specimens (epoxy/glass-PUF-epoxy/glass, polyester/glass-PUF-polyester/glass, and epoxy/glass-PUF-polyester/glass) were studied. Experimental results indicate that degradation of stiffness occurs due to debonding and sliding between the skin and the foam during fatigue cycles. Better performance of the epoxy/glass-PUF-epoxy/glass sandwich panels is most likely due to the superior properties of the outer thin skins. Most of the specimens failed within the foam region and not at the skin level due to debonding between the foam and the skin[18].

O. Konur and F.L Mathews[19] have shown that there is a close relationship between the properties of matrix, fibre and interface and thus affect the fatigue performance of the composite. Stiffness degradation during fatigue has been reported by many researchers[20-24, 13, 14]. Review of literature reveals that there is an ample scope for the study of fatigue behavior of sandwich structures by varying the core density and fabric architecture in facesheet. Thus the present work discusses the fatigue characteristics and the fatigue damage initiation and growth in different sandwich structures.

## 2. Experimental

### 2.1. Materials

The sandwich specimens used in the present study comprise of four different grades of E-glass fabrics (supplied by Vetrotex /Saint Gobian, India) in vinyl ester resin supplied by Ecmas, Hyderabad and three varied densities of polyurethane foam (PUF) core supplied by Polynate foams Pvt. Ltd. Bangalore. The sandwich specimen face sheet is synthesized by using 2% Cobalt Octate accelerator, Methyl Ether Ketone Peroxide (MEKP), Di Methyl Acetamide (DMA) and Vinyl ester. The fiber to resin volume ratio is maintained as 65:35. The samples are cured at room temperature for 24 hours followed by 70° C in oven for post curing. The sandwich specimen's specifications and various configurations used in the experiment are presented in Table 1.

### 2.2. Methods

#### 2.2.1. Flexural Test/Static Three Point bending Test

Flexural test was carried out according to ASTM C393. The dimension of the test specimen was 200 mm x 30 mm and overhang of 20 mm. The core thickness was 24mm and the facesheet thickness was 3mm. Tests were initially performed to get relevant load levels for the fatigue tests. Four identical specimens within each configuration were tested at room temperature, in a computer controlled universal testing machine at a constant displacement rate of 2 mm/min [Fig.1].

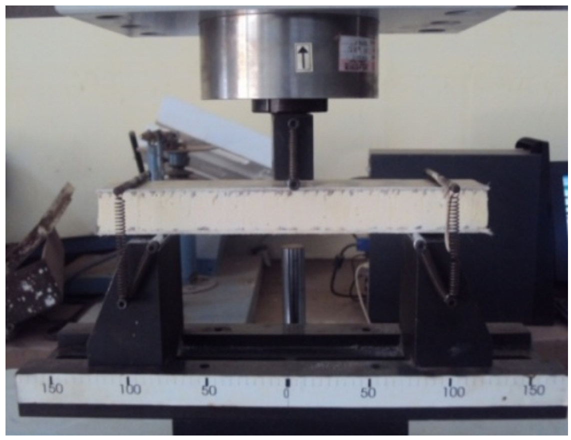


**Figure 1.** Three point bending setup

**Figure 2.** Specimen during fatigue testing

#### 2.2.2. Fatigue Lad Testing

Fatigue test was carried out according to ASTM C393. The fatigue tests were performed under a load controlled sinusoidal cycle using a servo hydraulic testing machine. The experiments were performed using 3 point bending as shown in Figure 2. The dimension of the test specimen was 200 mm x 30 mm and overhang of 20 mm. The core thickness was 24mm and the facesheet thickness was 3mm. The fatigue test frequency of 1Hz, 3 Hz, 5Hz, 7Hz and 9 Hz were chosen to observe any degradation of sandwich composites. The test was load controlled allowing the displacement to vary. The variation in displacement was closely monitored. 60% of ultimate bending load (Table 2) was chosen to predict the fatigue life of sandwich specimens. The tests were performed to failure or a maximum of $10^5$ cycles. The machine was set to stop automatically if the displacement during the test exceeded 20 mm either due to specimen failure or stiffness degradation to avoid damage caused to the setup.

**Table 1.** Sandwich composites – specifications

| Sandwich Type | Resin | Fabric Type (E-Glass) | Core Material | Core Density(Kg/m$^3$) |
|---|---|---|---|---|
| WR | Vinyl ester 3 mm | Woven Roving – 360 gsm | PU Foam (24 mm thickness | 100 - 300 |
| CSM | | Chopped Strand Mat-360 gsm | | |
| SBM | | Stitch Bond Mat -610 gsm | | |
| CSM (S) | | Chopped Strand Stitch Mat- 420 gsm | | |

# 3. Results and Discussion

## 3.1. Static Flexural Test

The maximum static bending load values of sandwich specimens with varied fibre architecture and density are presented in Table 2. The static flexural test results show that the flexural stress increases with increase in core density.

**Table 2.** Ultimate bending load (N) at failure for various sandwich specimens

| Sl. No. | Density (kg/m$^3$) | CSM | CSM-S | WR | SBM |
|---|---|---|---|---|---|
| 1 | **100** | 149 | 145.19 | 156 | 146.40 |
| 2 | **200** | 195.6 | 193.97 | 222.5 | 214.44 |
| 3 | **300** | 219.18 | 213.23 | 261.10 | 226.05 |

Bending strength at the ultimate bending load of sandwich specimens with varied fibre architecture and change in density under flexural test is presented in Table 3. The static flexural test results show that the flexural strength of the sandwich composites is dictated by density parameter.

**Table 3.** Facing bending strength (FBS) (MPa) for various sandwich specimens

| Sl. No. | Density (kg/m$^3$) | CSM | CSM-S | WR | SBM |
|---|---|---|---|---|---|
| 1 | **100** | 2.44 | 2.39 | 2.57 | 2.41 |
| 2 | **200** | 3.22 | 3.19 | 3.66 | 3.53 |
| 3 | **300** | 3.61 | 3.51 | 4.30 | 3.72 |

## 3.2. Fatigue Test

The fatigue life is characterized as the number of cycles to ultimate failure. There were no visual signs of damage in the specimens prior to specimen failure, but nearing to $10^5$ cycles the damage occurred abruptly. The stiffness of the specimens under lower testing frequencies exhibited no measurable change until the final load cycles prior to complete rupture. Figure 2 illustrates the still photograph of the fatigue testing, the bending of the sandwich can be clearly seen.

The Wohler's (S-N) curve for the four types of the sandwich specimens at five different test frequencies are given in Figures 3 -7. The fatigue behavior is found to be similar in all the four types of sandwich composites. A linear trend in fatigue curve is observed up to certain working cycles, later the trend shifts causing partial or complete collapse of the specimens.

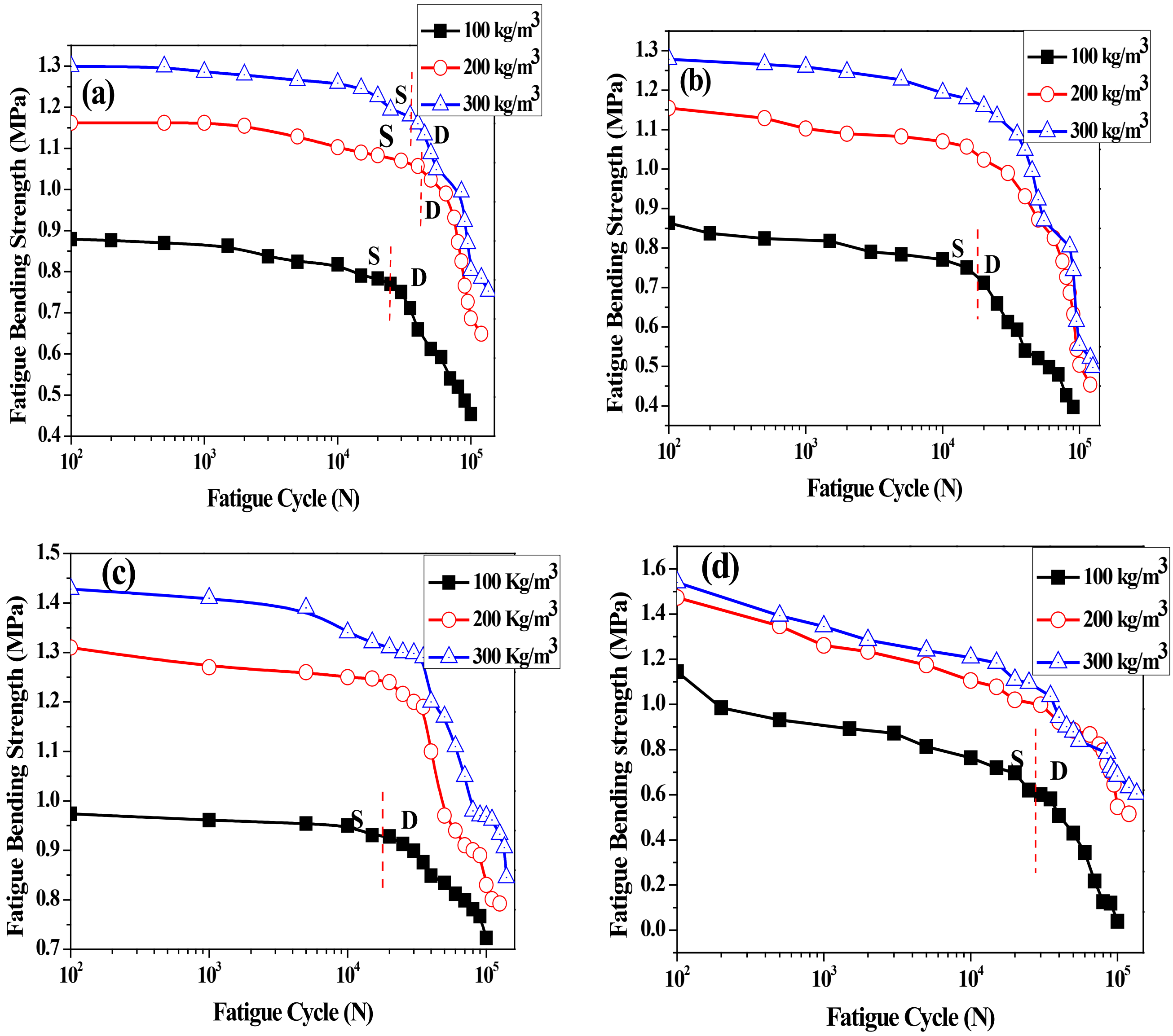
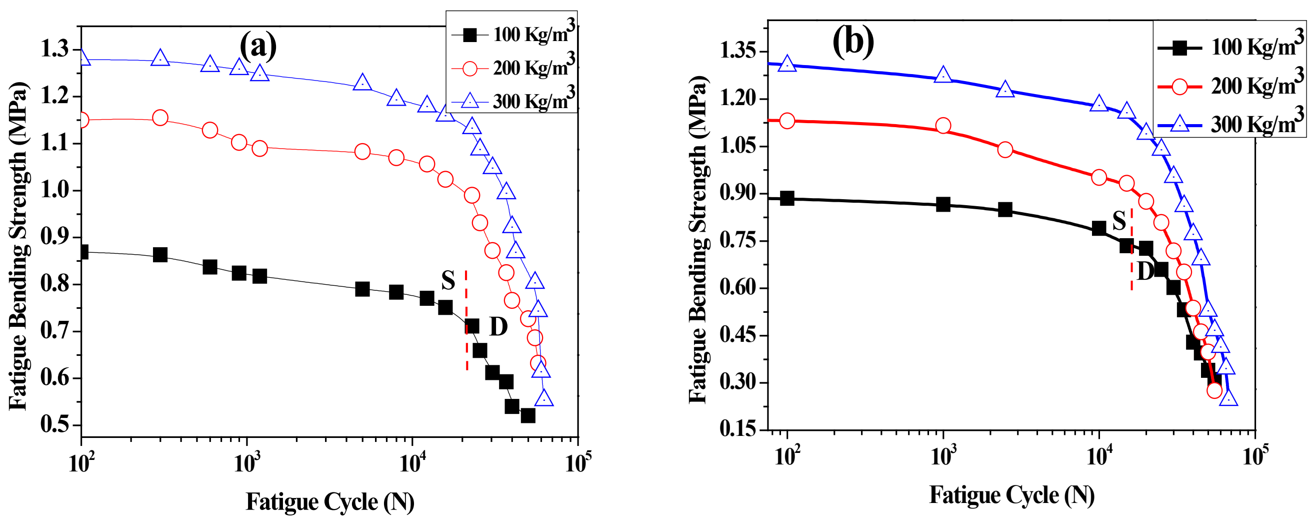



**Figure 3.** Fatigue plots of sandwich composites at 1 Hz frequency. a)- CSM, b) CSM-S, c)-WR d) SBM



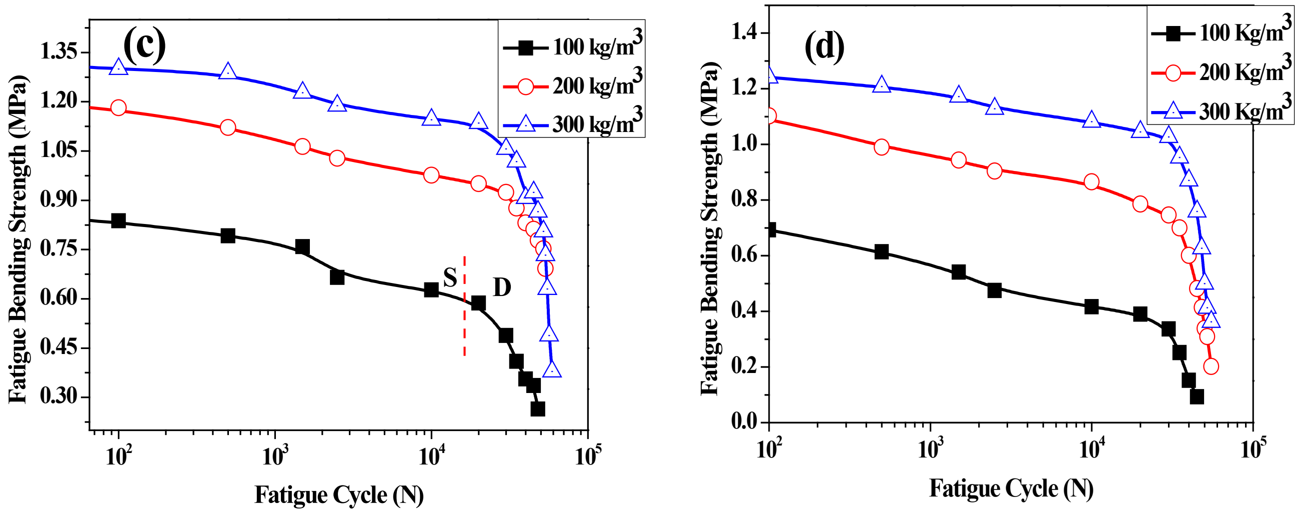



**Figure 4.** Fatigue plots of CSM-S sandwich composites at frequencies a) 3Hz b) 5Hz c) 7Hz d) 9Hz

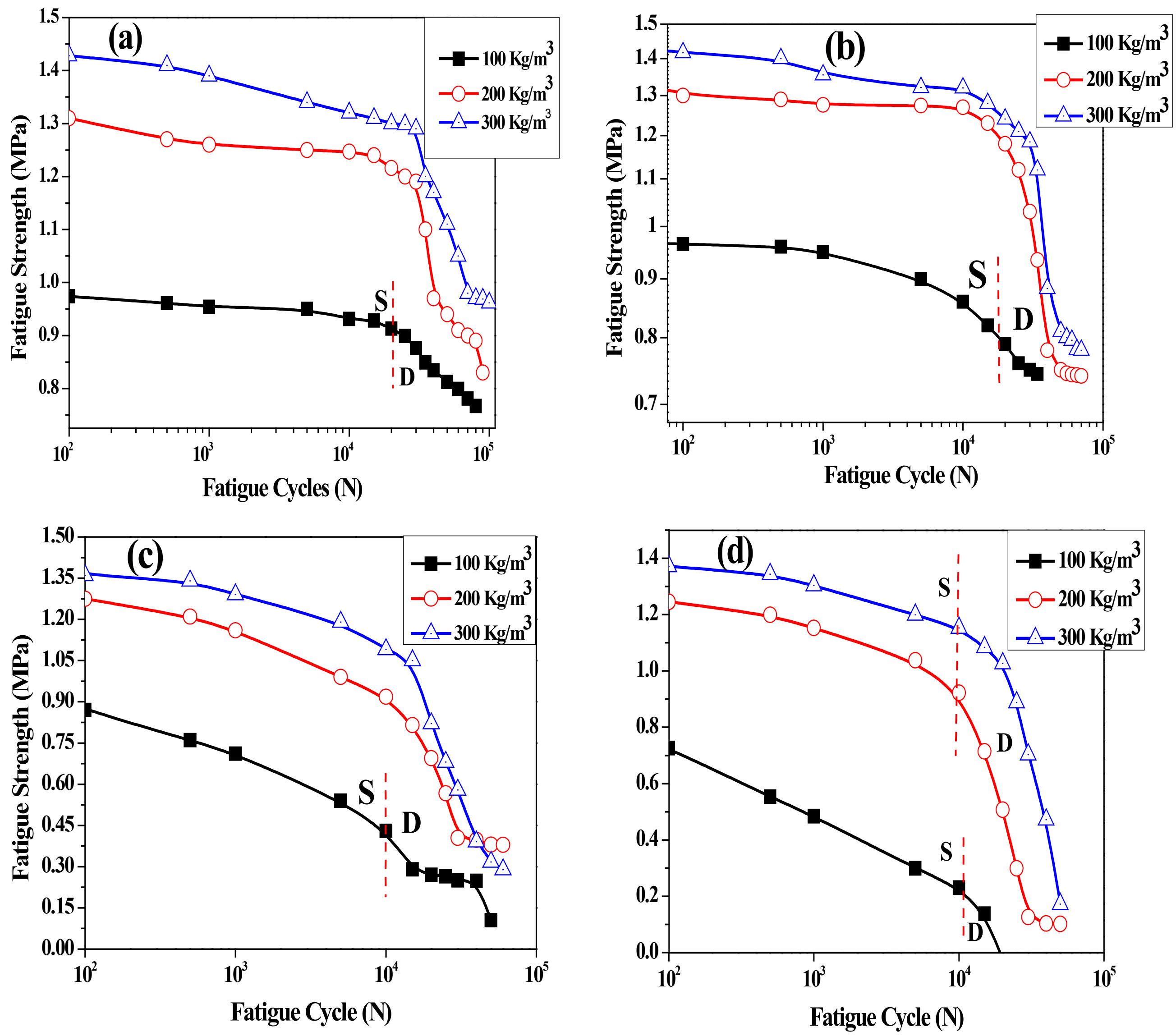



**Figure 5.** Fatigue plots of WR sandwich composites at frequencies a) 3Hz b) 5Hz c) 7Hz d) 9Hz

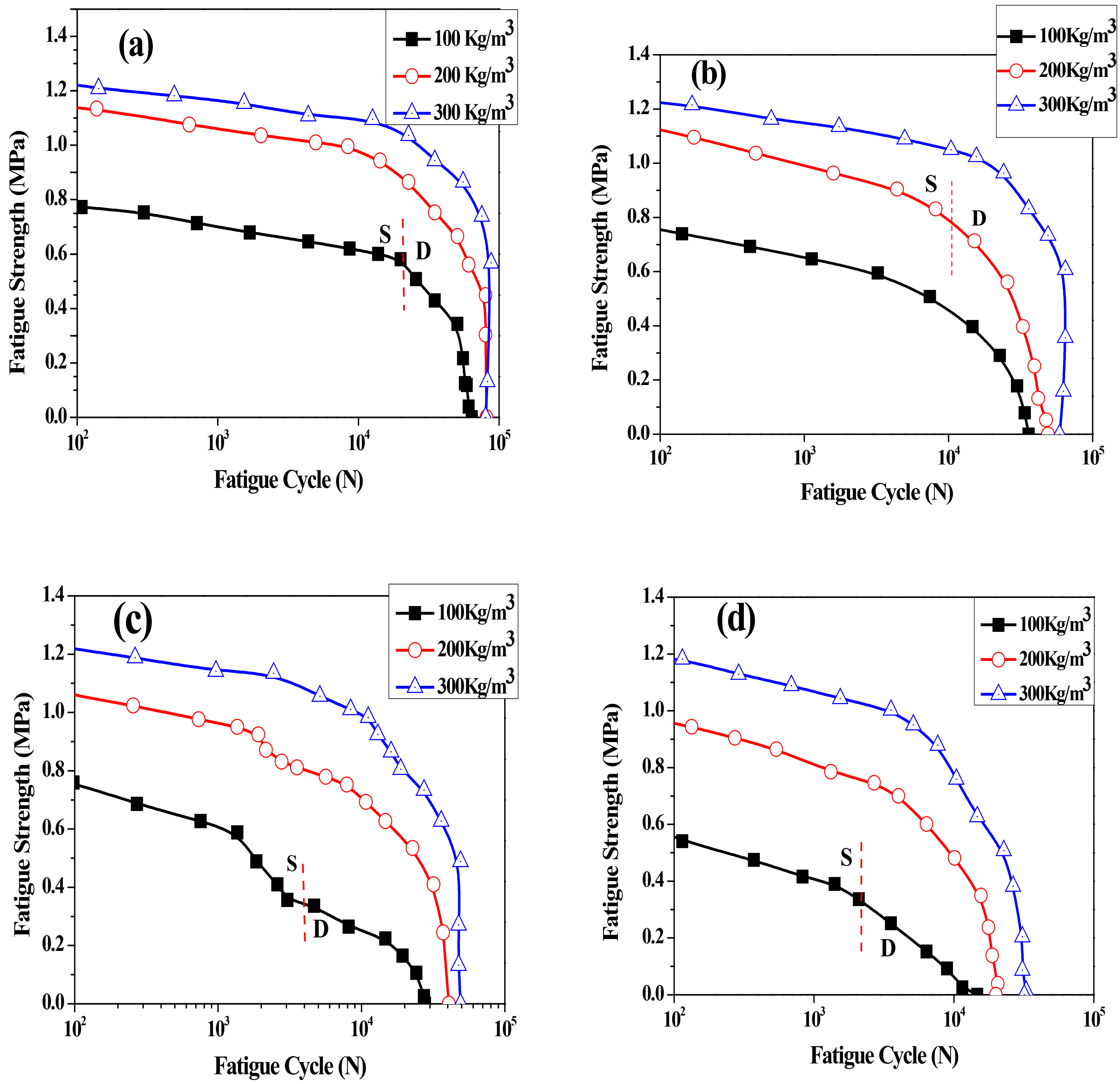



**Figure 6.** Fatigue plots of SBM sandwich composites at frequencies a) 3Hz b) 5Hz c) 7Hz d) 9Hz

At frequencies 1Hz and 3 Hz the specimens did not fail completely when the machine was stopped. It was observed that all the specimens offered a high resistance against the fatigue load and least damage at 1 Hz. The test was stopped at a deflection of 20 mm, the maximum deflection that can be attained. Though the specimens at 1 Hz were able to complete $10^5$ working cycles, there was marginal degradation of the core, as evidenced from the decrease in the fatigue strength. At 3 Hz and 5 Hz working cycles, samples were found to be damaged, but all the samples completed the set load cycles. At lower frequencies (up to 5Hz), no flaws were observed in the specimens, but a gradual decrement in the strength and enhancement of degradation rate, nearing to $10^5$ cycles. At 7 Hz and 9 Hz frequencies the specimens failed and could not reach the expected $10^5$ cycles. However CSM-S-300 and WR-300 sandwich composites reached almost $10^5$ cycles. Although samples exhibit core failure, it is found that samples take some load till its complete failure. All the samples have undergone damage at 9 Hz frequency. The stints of powdery foam started to evolve from the mid span of the core indicating the existence of core shear under cyclic loading. At higher test frequencies some specimens exhibited cracking and tearing noise before proceeding into typical failure modes. Fatigue strength increased with increase in the core density. The failure of the sandwich specimens with higher density foams occurred at higher cycles. It can be seen from the plots Fig. 4 (a & b) that degradation initiated at much earlier cycles at high frequencies with increase in the density of the foams.

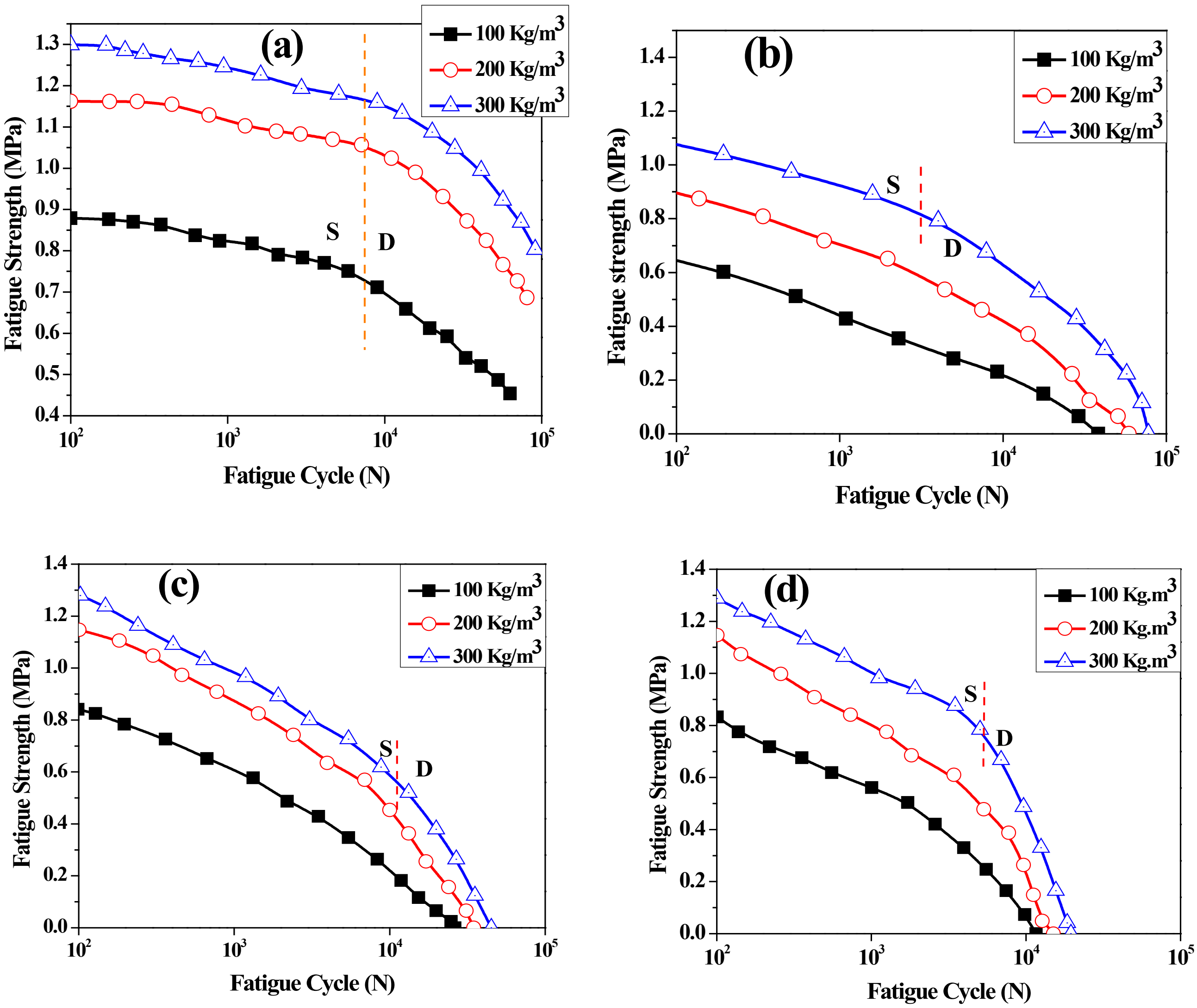



**Figure 7.** Fatigue plots of CSM sandwich composites at frequencies a) 3Hz b) 5Hz c) 7Hz d) 9Hz

**Table 4.** The transition point and failure modes observed under fatigue testing

| Sandwich Type | Fatigue Behavior observed at 60% of Ultimate loading | | | | | Failure mode observed |
|---|---|---|---|---|---|---|
| | Density of PU Foam ($Kg/m^3$) | Cycle to failure (MPa) | | Stiffness Degradation (%) | | |
| | | Lower Cycle (3 Hz) | Higher Cycle (9 Hz) | Lower Cycle (3 Hz) | Higher Cycle (9 Hz) | |
| Woven Roving | 100 | 16350 | 8186 | 27 | 51 | Debonding, Core Crack, Delamination |
| | 200 | 21360 | 8900 | 20 | 42 | |
| | 300 | 27980 | 14050 | 17 | 34 | |
| CSM | 100 | 14648 | 1923 | 35 | 59 | |
| | 200 | 16650 | 3219 | 23 | 45 | |
| | 300 | 17507 | 4885 | 22 | 39 | |
| CSM-S | 100 | 12428 | 9860 | 33 | 53 | |
| | 200 | 21354 | 22150 | 20 | 39 | |
| | 300 | 30050 | 26064 | 16 | 37 | |
| SBM | 100 | 21354 | 22150 | 31 | 54 | |
| | 200 | 30050 | 26064 | 22 | 40 | |
| | 300 | 16156 | 3455 | 19 | 43 | |

**Table 5.** FBS and CSS (MPa) for various sandwich specimens

| Sl. No. | Density ($kg/m^3$) | CSM | | CSM-S | | WR | | SBM | |
|---|---|---|---|---|---|---|---|---|---|
| | | FBS | CSS | FBS | CSS | FBS | CSS | FBS | CSS |
| 1 | **100** | 1.46 | 0.09 | 1.43 | 0.09 | 1.54 | 0.09 | 1.44 | 0.09 |
| 2 | **200** | 1.93 | 0.11 | 1.94 | 0.12 | 2.20 | 0.13 | 2.12 | 0.13 |
| 3 | **300** | 2.17 | 0.13 | 2.10 | 0.13 | 2.58 | 0.16 | 2.23 | 0.14 |

The fatigue behavior of all the sandwich composites exhibited a transition point, i.e., transition from a steady stable state region (S) to a deteriorating region (D) at which there is a sudden change in the slope.

In the region S, there is a marginal decrease in the fatigue strength. The debonding between facesheet and foam did not significantly affect the fatigue life behavior of sandwich specimen keeping the rate of stress almost constant. The cycles at which S to D transition observed is given in Table 4.

At higher frequencies, the transition point is observed at lower cycles. Also, as the density of the foam increased the transition point is observed at higher cycles. After the transition point, the specimens exhibited crack between the foam and the facesheet. Rate of decrease in fatigue strength is found to be more in the case of CSM sandwich composites and minimum for CSM-S and WR sandwich composites.

WR sandwich composites possess highest fatigue strength. The higher fatigue strength when compared to the other sandwich composites may be due to its highest bending strength and hence can resist high compressive and shear strength occurring during cyclic loading. A combination of high shear and compressive properties at the interface may be the reason for the higher fatigue strength in WR sandwich composites. The bending strength of the sandwich composites depends mainly on the strength of the facesheets, foam core and the interfacial bonding between the facesheet and the foam. Core shear strength (CSS) and facing bending strength (FBS) at 60% of the ultimate bending load are given in Table 5.

M. Kharwar Farooq et al.,[25] have analyzed the flexural behavior of sandwich composites with PVC core and glass/epoxy face sheets under fatigue. They observed initiation of damage in the facesheet and compression in the core at few hundreds of cycle. With the increase in number of cycles, these damages propagated and interfacial debonding initiated between the facesheet and the core. This damage mechanism continued with increase in number of cycles resulting in complete debonding between the top facesheet and the core. Frequency in the range of 0.1-10Hz had no significant effect on stiffness degradation. Stiffness degradation increased with increase in core thickness. The effect of density of PVC core on the fatigue behavior of $S_2$ glass fibre reinforced vinyl ester sandwich composites has been reported by K. Kanny & H. Mahfuz[4]. The stiffness and failure load of sandwich beams increased with increased core density and fatigue strength decreased with increased stress and increased with core density. Fatigue failure post test analysis of PU foam cored-carbon fibre/ epoxy sandwich composites by Basir Shafique and Amilear Quispitupa[26] indicates core failure as the predominant damage mechanism followed by the interfacial failure.

S.C Sharma et al.,[27, 28] have studied the fatigue behavior of polyester /glass/ PU/ glass/epoxy, Epoxy/glass/ PU/glass/epoxy and Polyester/glass/PU/glass/polyester sandwich composites. Epoxy/glass/PU/glass/epoxy sandwich structures exhibited highest fatigue strength along with higher stiffness degradation compared to other two types of sandwich panels. Lowest fatigue properties were obtained for polyester/glass/PU/glass polyester sandwich specimens with lower stiffness degradation. Most of the specimens failed within the foam region and not at the facesheet level due to debonding between facesheet and core. At 1Hz none of the specimens failed. Above the transition points, numerous cracks were seen between the foam and the facesheet. In the deteriorating region, debonding between the facesheet and the foam core played a major role. Stiffness degradation increased with the increase in the fatigue frequency. The three failure modes observed were facesheet failure due to delamination, shear failure in the core and facesheet /core interface and core failure due to crushing stresses. Stiffness degradation was around 40% for epoxy and 30 % for polyester sandwich composites. The fatigue strength and stiffness degradation were mainly dependent on interfacial bond strength. In the initial cycles of fatigue loading, interfacial bond strength was stronger, but gradually weakened at higher cycles because of rubbing at the interface between the facesheet and the foam.

Fatigue crack growth and life prediction of PVC foam cored $S_2$ glass epoxy sandwich composites under flexural loading have been studied by N. Kulkarni et al.[5, 16] They observed that the fracture failure of the sandwich composite was controlled by the failure of the core. Crack propagation occurred in three stages i.e., core- facesheet debond, core shear followed by another core-facesheet debond. The first stage constituted around 85% of the fatigue life. Degradation in stiffness was only about 10%. The fatigue behavior of PUF 3-D woven glass fabric epoxy sandwich composites has been investigated by H. Judiwistra et al.[29]. The 3-D woven glass fabric epoxy panels with PU foam showed excellent fatigue behavior and low stiffness degradation. Fatigue life was higher than $10^6$ cycles and stiffness degradation lower than 6% at 80% bending ultimate load.

### 3.3. Damage Formation During Fatigue Testing

It is observed that the fatigue life of sandwich structures solely depend on shear strength in the structure. In three-point bending, besides shear stresses, tension and compression stresses are also generated in the core. Hence tension and compression stresses play a significant role resulting in lower shear strength. During fatigue testing the sandwich specimens are repeatedly undergoing tensile and compressive stresses at bottom and top facesheets respectively. This stress builds up shear stresses in the sandwich assembly. The ability of the core to balance theses stresses dictates the fatigue life of any sandwich composite. Maximum shear stress is observed at the centre of the core, where the compressive stress balances the tensile stress. Fracture initiates at the centre of the core and there is a rise in temperature in the core. During compression and tension cycles, there will be an increase in the temperature at the interface due to the friction between the facesheet and core[4]. The high shear stress along the centre of the core causes micro cracks or irregularities to initiate which only could be observed visually at a very late stage of the fatigue life of the specimen. These micro cracks eventually grow in number and start to interact with each other forming a horizontal crack which eventually separates core from the facesheets.

The fracture mechanics involved in sandwich composites under fatigue loading is complex and is associated with more than one failure modes due to anisotropic behavior of facesheets. Generally sandwich composites experience progressive fatigue degradation due to failure of the fibres, fibre stacking sequence and type of fatigue loading. The damage development under fatigue and static loading is similar but with the exception that the fatigue loading at a given stress level will cause additional damage and this will be dependent upon the cycle frequency[30]. The failure mechanisms observed under fatigue testing of sandwich composites are; i) Fibre breakage-interface de-bonding, ii) Matrix Cracking, iii) Interface shear failure with fibre pull-out iv) Delamination. Any combination of the above four is possible and may cause fatigue damage which may result in reduced fatigue strength and stiffness. The degree of fatigue damage is highly dependent upon material properties, facesheet, stacking sequence, applied load and number of cycles[30].

At high fatigue stress, cracks can initiate on the first loading cycle and will then accumulate with increasing number of cycles. However cracks can develop even when the maximum cycle stress is well below the static cracking threshold of cycles but these cracks will not take place until after many cycles, the actual number depends upon the peak stress. Early initiation of matrix cracking in fatigue relative to static loading will lead to a decrease in the threshold for the onset of other types of damage. Delamination can propagate over many thousands of cycles thus resulting in separation of the laminate into discrete laminae which will continue to support the fatigue loading.

Figures 8 and 10 illustrate the various modes of sandwich failure during fatigue loading as a function of frequency and number of cycles for low and high density sandwich composites observed in the present study.

In low density sandwich composites, the crack path in the core at low frequencies is different from that at higher frequencies. However, the crack path in high density sandwich composites is similar at lower and higher frequencies (Fig.10). K. Kanny et al.[4] have also observed that in low density sandwich composites, crack path in the core at lower frequencies is different from that at higher frequencies and the crack path in high density sandwich composites is similar at lower and higher frequencies.

Fatigue failure is as a result of the combination of tension, compression and shear stresses. In low density sandwich composites (up to 200 kg/m$^3$), at lower frequencies i.e., up to 5 Hz, initiation of the damage in the facesheet and compression in the core occur at few hundreds of cycles. With increase in the number of cycles, interfacial debonding in the upper facesheet/core results. This phase represents 75% of the fatigue life. During this period, only the core and the bottom facesheet could bear the applied load. With further increase in the number of cycles, debonding starts at the lower facesheets also. At higher cycles, i.e., in the 'D' region cracks in the core is initiated at one side and propagated diagonally at 55° to the other side (Fig.8 a, b). Final stage involves delamination. M Kharwar Farooq et al[25] have observed similar failure modes in the case of PVC core/glass/epoxy sandwich composites under fatigue. But at higher frequencies and lower cycles first stage involves crack initiation and propagation on the compression side just below the facesheet/core interface and the second stage is core shear and core crack propagation diagonally towards the tensile side and finally crack formation at the tensile side of the sandwich just above the core/facesheet interface. At higher frequencies and higher cycles, crack propagates on the other side of the roller (loading point arrangement on the sandwich specimen) reaching the lower facesheet (Fig.8 c &d), resulting in delamination and debonding of the core/ facesheet interface. In PVC cored S2 glass fabric/epoxy sandwich composites S. Kulkarni et al[5, 16] have observed initial stage as crack initiation and propagation on the compression side just below the top facesheet/core interface. Delamination crack was about 1-1.5 mm below the interface. This was followed by core shear and third stage was delamination at bottom facesheet/core interface causing the separation of core from the facesheet.

The photographs of the failed low density sandwich composites under fatigue are given in Fig.9 (a & b).

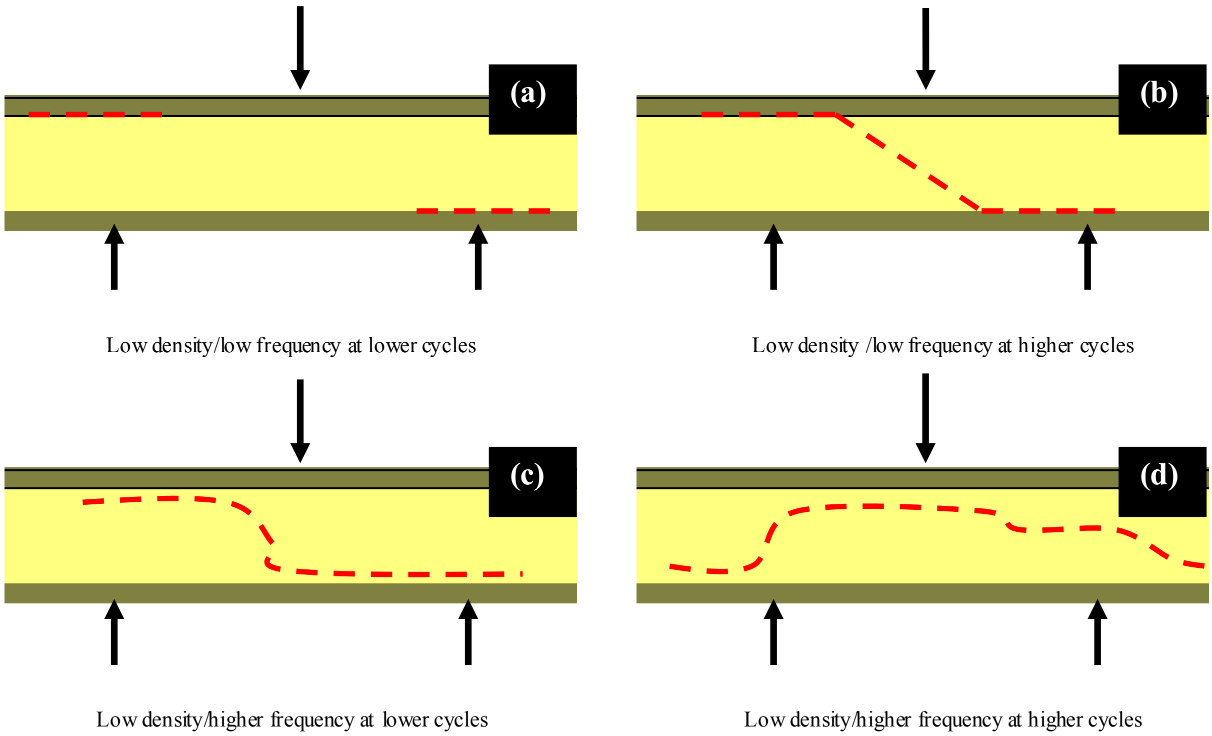



**Figure 8.** Failure modes of low density sandwich composites under fatigue loading

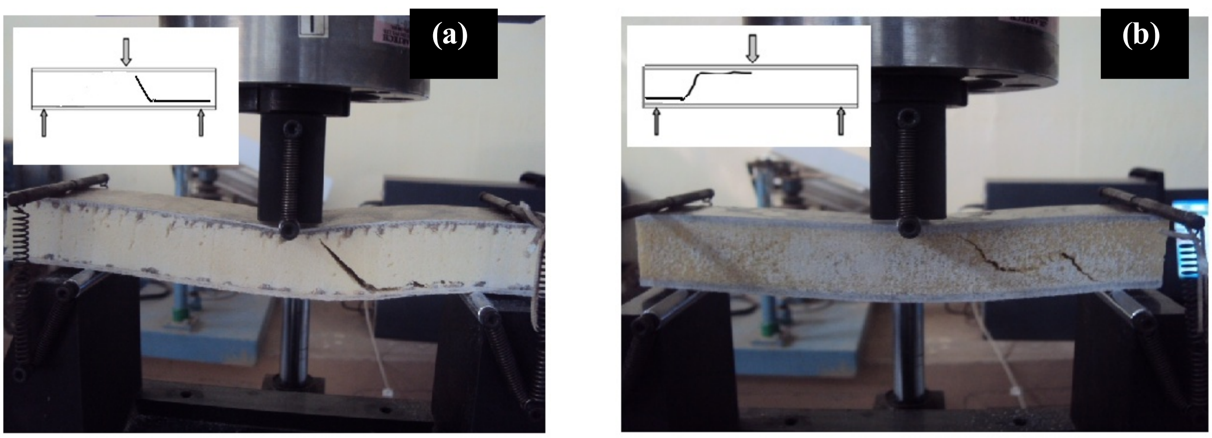



**Figure 9.** Failure of low density sandwich composites

With higher density composites (300 Kg/m$^3$) at low frequencies and lower cycles, crack is initiated in the region of high shear stress i.e., in the middle of the core. The cracks nucleate at much faster rate due to repeated impact contact of the roller with the sandwich specimen. Micro cracks are formed in the beginning and finally grew to a macro crack as shown in the Figure 10(a).

The macro crack formed is propagated at 55° towards one side of the facesheet/core interface. As the number of cycles increased, the macro crack propagated to the other facesheet/core interface, resulting in delamination and debonding (Fig. 10 b & Fig 11 e). Similar type of failure mechanism has been observed in PVC cored glass reinforced vinyl ester by Burman & Zenkert[7]. But at higher frequency and lower cycles, crack is formed in the core and propagated towards upper and lower facesheets. The direction of crack propagation is 55° to the original crack (Fig. 10 c). The specimens showed visible cracks in the mid height of the core. Grenesdelt et al.,[11] have observed the crack propagation angle ranging from 65° to75° in expanded PVC foam materials of different densities. In PVC cored glass epoxy sandwich composites, Burman & Zenkert[7] have reported that the angle at which the cracks kinked at final fracture was different for each crack ranging between 55°and 85°. As the number of cycles increased, micro cracks are initiated adjacent to the major crack formed in the middle of the core (Fig. 10 d). Multiple cracks are formed due to the large difference in the elastic properties of the constituents of sandwich composite ($E_{facesheet} \gg E_{interface} > E_{core}$)[26]. At higher cycles, delamination and debonding of foam/facesheet occur very rapidly. Some specimens exhibited cracking and tearing noise was heard. The photographs of the failed high density sandwich composites are given in Fig.11 (a-e).

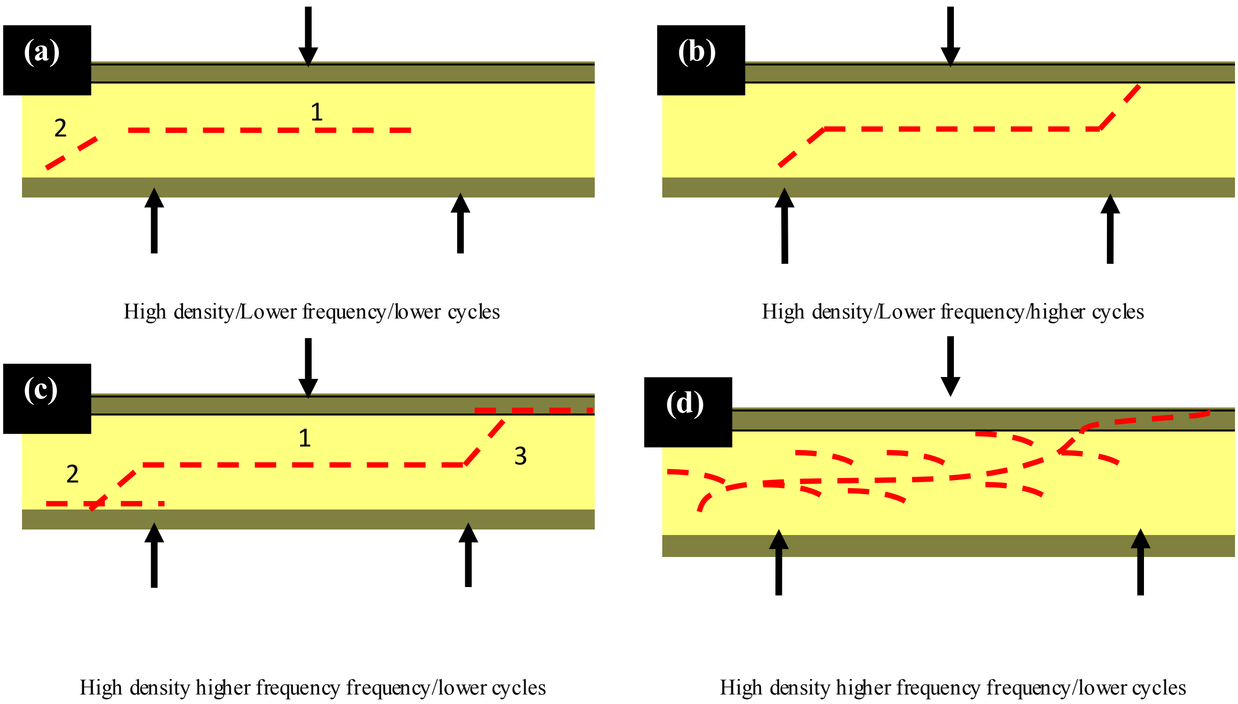



**Figure 10.** Failure modes of high density sandwich composites under fatigue loading

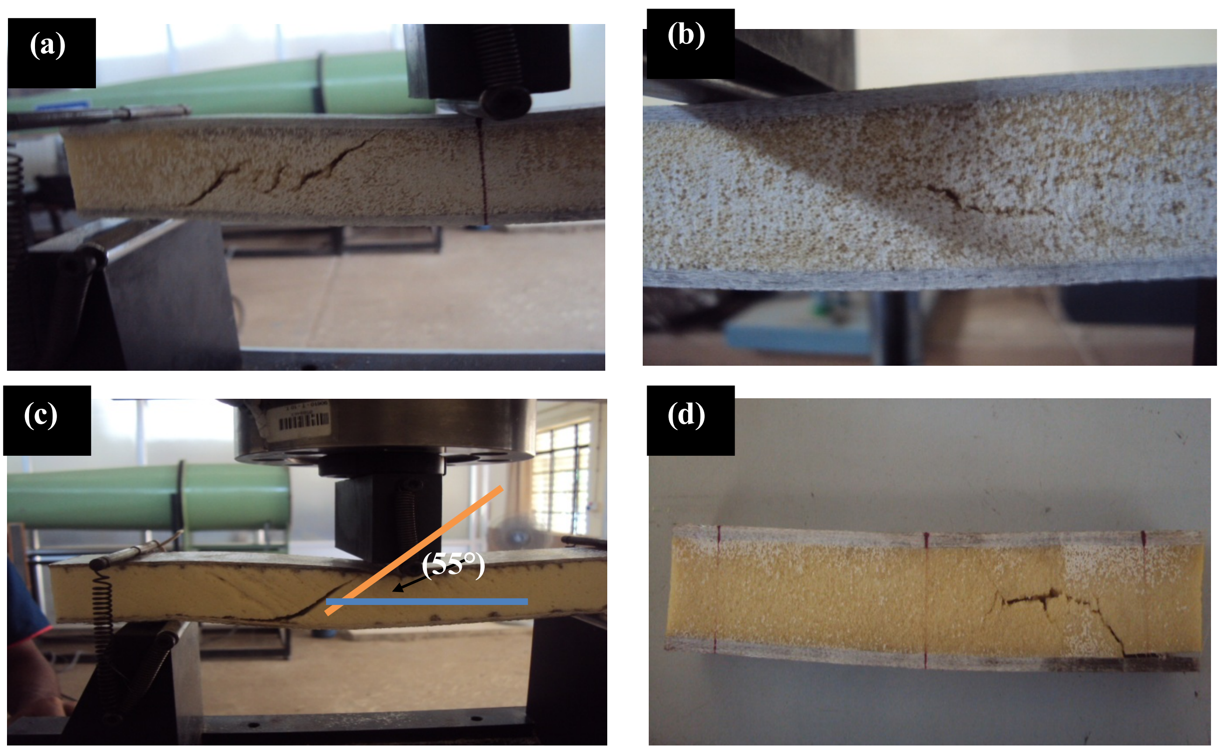



**Figure 11.** Failure of high density sandwich composites

In lower density sandwich composites, first stage of the failure involves debonding at the upper and lower facesheets and in the second stage core crack initiates near the interface between the facesheet and core on one side and propagate diagonally at 55° angle towards the other side. However, in high density sandwich composites, crack is initiated at the mid height of the core which moves diagonally at 55° upwards and reaches the other facesheet, thus balancing the shear stress. The second and third stages are characterized by delamination and debonding of the facesheet from the foam core. Higher core temperature at higher frequency may be the reason for the difference in the crack path at low and high frequencies in low density sandwich composites. High density sandwich composites are more dense and hence no difference in crack path at low and high frequencies. Sandwich composites with low density exhibit ductile behavior whereas sandwich composites with high density exhibit brittle characteristics. Hence the crack is initiated near the core /facesheet interface in low density sandwich composites and in the middle of the core in high density sandwich composites.

Thus damage formation and failure modes in the present system are dependent on the density of the foam core, loading frequency, number of cycles and fibre architecture. Crack path and crack propagation depend on the density of the core, loading frequency and number of cycles. Fatigue strength depends on the fibre architecture and density of the foam. WR sandwich composites possess highest fatigue strength. The higher fatigue strength when compared to the other sandwich composites may be due to its highest bending strength and hence can resist high compressive and shear strength occurring during cyclic loading.

The sandwich specimens used in the present study comprised of fibres which are i) bi-directional woven roving mat, which has 0°/90° orientation ii) randomly oriented chopped strand mat iii) Chopped strand stitch mat and iv) stitch bond mat. Woven roving mat has 0°/90° orientation and the regular pattern is repeated which offers resistance to fatigue loading. CSM mat consists of chopped fibres randomly oriented and CSM-S mats are stitched CSM mats. The discontinuous fibre composites have lower strength compared to directional composites due to less efficient utilization of fibres and stress concentration effects of fibre ends. Hence damage develops at fibre ends and causes failure at shorter life time. Therefore CSM-S and CSM composites have lower fatigue strength. In the case of SBM fibre mat, an woven roving mat is stitched on to a CSM mat. Therefore the orientation of the fibre is similar to that of woven roving mat on one side and that of CSM on the other side. Because of this heterogeneity, the fatigue behavior is inferior to WR mat[31].

The fatigue life/strength of higher density PU foam composites are higher compared to low density sandwich composites. The varied PU foam density is caused by varying the proportion of chemicals and the foam is formed by chemical reaction between polyol and MDI. The number of cells per unit area increases as the density of the foam increases[32]. The larger number of cells per unit area in high density sandwich composites may be the reason for the long fatigue life in high density sandwich composites.

### 3.4. Stiffness Degradation

The variation of the stiffness during the major part of the lifetime was insignificant. The time (or number of cycles) from crack initiation to final fracture was short relative to the fatigue life in the case of all sandwich composites. During the last part of the fatigue life the degradation was more pronounced.

The stiffness degradation (%) is calculated by using the following equation.

Stiffness degradation (SD) =

$$\frac{(\text{Slope at first cycle} - \text{Slope at final cycle})}{\text{Slope at first cycle}} x100$$

$$SD = \frac{\left(\frac{\Delta P}{\Delta\delta_{Firstcycle}}\right) - \left(\frac{\Delta P}{\Delta\delta_{Ncycle}}\right)}{\frac{\Delta P}{\Delta\delta_{FirstCycle}}} \text{X100}$$

where $\Delta$P is the difference between maximum and minimum loads (N) and $\Delta\delta$ is the specimen displacement in mm due to $\Delta$P.

Stiffness degradation increased with increase in fatigue frequency. Stiffness degradation starts at lower cycles as the frequency is increased. Stiffness degradation decreases with increase in the density of PU foam. The stiffness degradation occurred at higher cycles in high density sandwich composites (Fig.12). At higher fatigue cycles, damage to the interface between foam and facesheet occurs very rapidly and stiffness decreases. WR sandwich composites exhibited the highest fatigue strength and the minimum stiffness degradation. In all the specimens 'S' region decreased with increase in fatigue frequency. It is due to an increase in strain at higher frequencies. At the interface, foam material crushed out from the facesheet as small pieces and bending strength decreases at higher frequencies. Stiffness decreases with the increase in frequency and number of cycles due to various damages developed in the facesheet and core.

As the sandwich deteriorates, cracks are nucleated between the facesheet and the foam, facesheet bears smaller load while foam takes the major portion of the load. Due to the imbalance in the load sharing, foam loses its stiffness, thereby increasing the stiffness degradation. At higher fatigue frequency, fatigue behavior of both side specimens is found to have higher stiffness degradation. Thus fatigue load and frequency are the major parameters that affect the degradation in stiffness.

The stiffness of sandwich structure depends on the interfacial bond strength which may be reduced by partial delamination of foam core and facesheet. During compression and tension cycles, the facesheet and foam core rub against each other, leading to an increase in temperature at the interface. The interfacial temperature increases with the increase in the frequency of the fatigue cycles due to less time for heat dissipation. The stiffness decreases with this increase in temperature at the interface, hence stiffness degradation of all the specimens increase with increasing fatigue cycle frequency. This degradation leads to failure of sandwich composites as a result of debonding of the facesheet/core and fibre rupture. Fiber rupture leads to severe facesheet stiffness reduction. Basir Shafiq & Amilear Quispitupa[26] have observed substantial weakening of the constituents of sandwich composites as a result of damage to core and interface and fibre rupture in urethane foam core carbon fibre sandwich composites

The stiffness degradation is minimum for WR samples and maximum for CSM samples. At 9 Hz frequency the stiffness degradation was around 50% for WR sandwich specimen and 60% for CSM sandwich composites. The stiffness degradation is due to various damages occurring in the specimen, as evidenced from photographs & SEM micrographs.

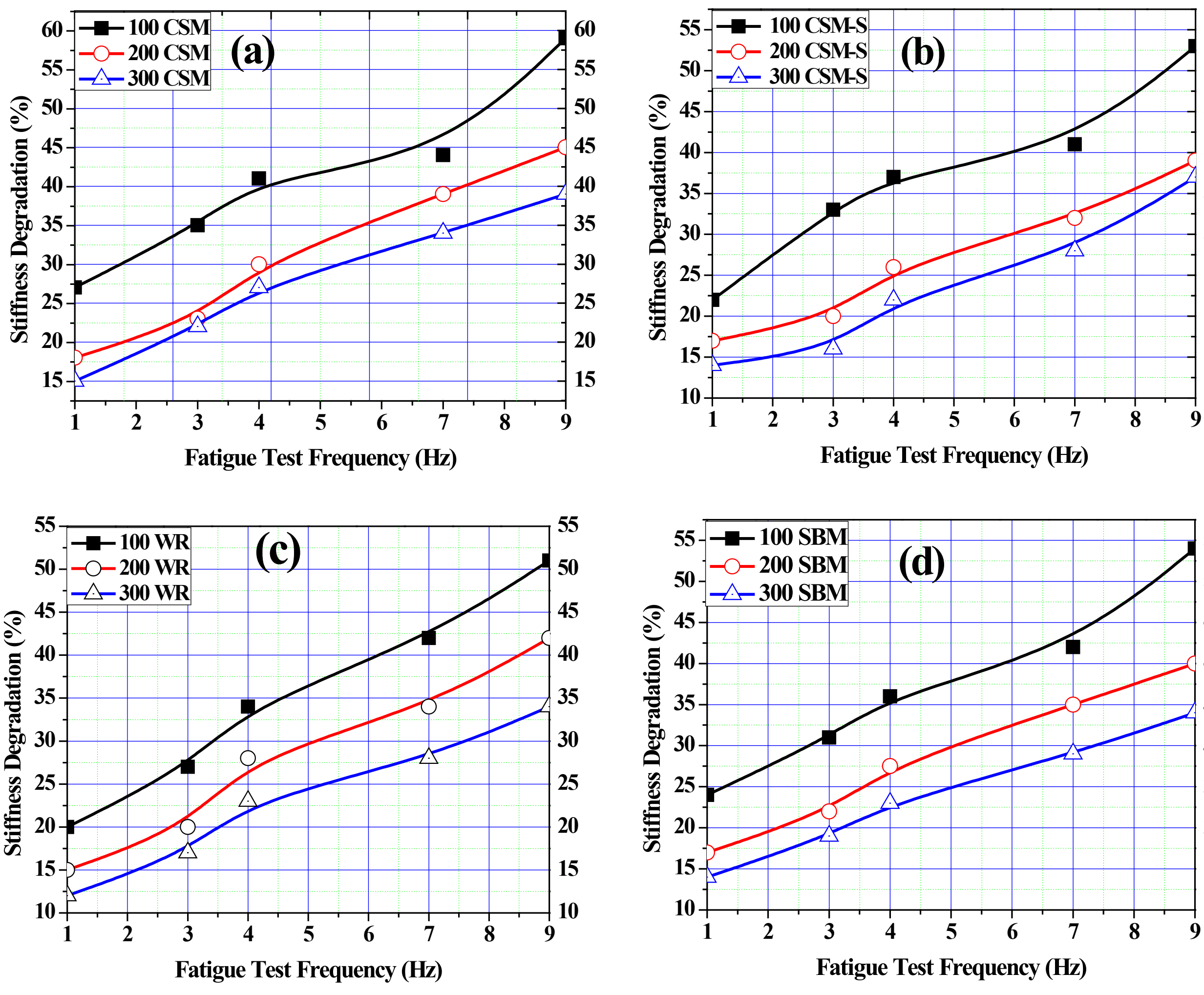
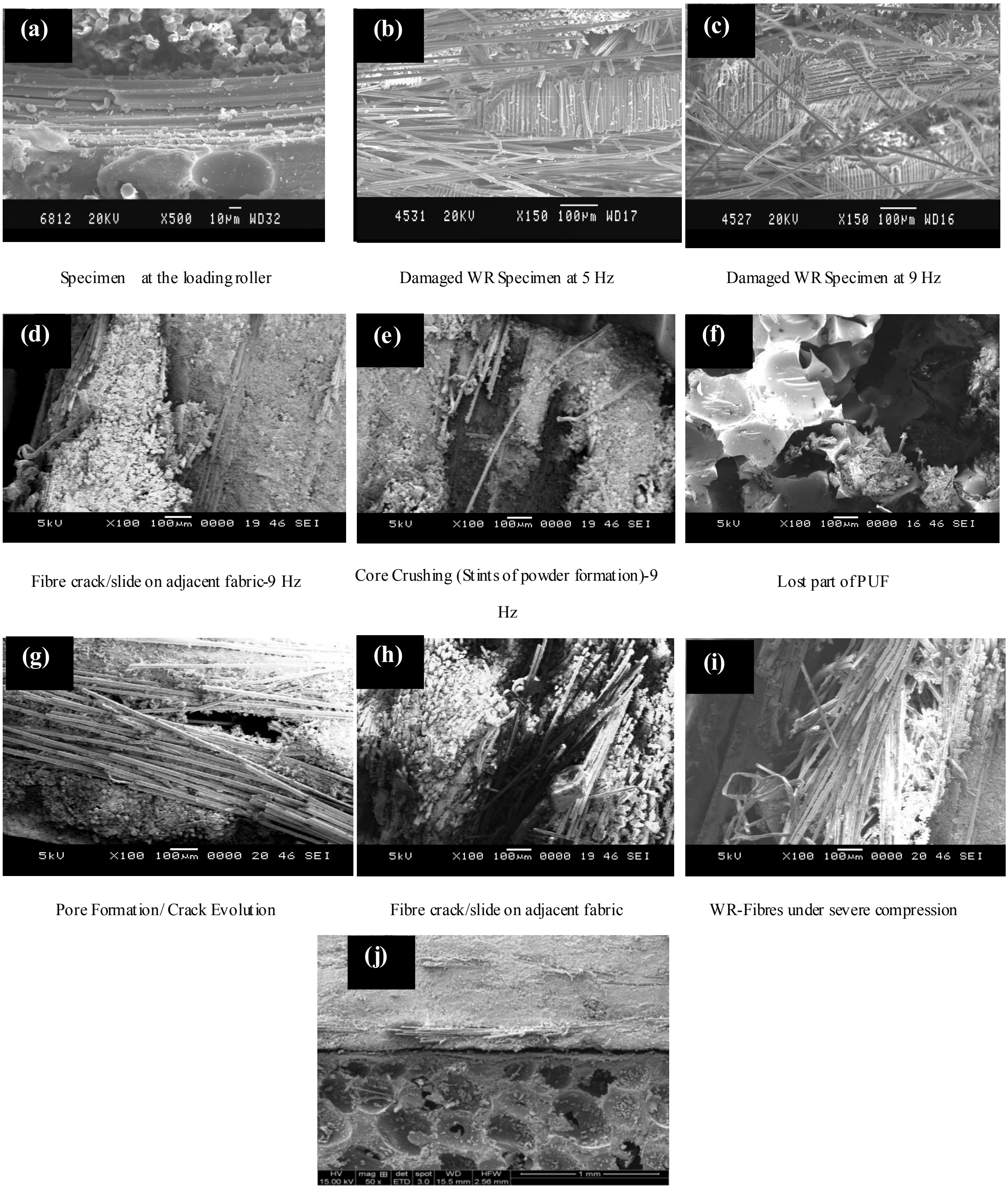



**Figure 12.** Stiffness degradation in sandwich composites a) CSM, b) CSM-S, c) WR and d) SBM

### 3.5. SEM Analysis




(a) Specimen at the loading roller

(b) Damaged WR Specimen at 5 Hz

(c) Damaged WR Specimen at 9 Hz

(d) Fibre crack/slide on adjacent fabric-9 Hz

(e) Core Crushing (Stints of powder formation)-9 Hz

(f) Lost part of PUF

(g) Pore Formation/ Crack Evolution

(h) Fibre crack/slide on adjacent fabric

(i) WR-Fibres under severe compression

(j) Facesheet/core debonding

**Figure 13.** The SEM images of the sandwich composites

SEM micrographs of the damaged WR sandwich composites are shown in Fig. 13. Fig. 13(a) shows the failed specimen under the roller when observed from the surface. Fig. 13(b &c) show the surface view of the damaged WR sandwich specimens under the roller at 5 Hz and 9Hz working frequency respectively, where, disintegration of fibre and matrix are observed. Fig. 13(d&e) is the SEM image of the interface at 9 Hz. At the interface fibre crack and core crushing is observed. Fig. 13(f-i) gives the cross sectional view of the failed composites at 9 Hz. Pore formation and crack evolution at the interface, foam crushing, fibre under severe compression, fibre disintegration are observed at 9Hz frequency. Fig. 13(j) shows debonding at 9Hz frequency.

# 4. Conclusions

- At 1 Hz & 3 Hz frequencies, the specimens didn't fail completely, but at 9 Hz, the specimens failed due to delamination & core crack.
- The fatigue failure of the sandwich composite is controlled by failure of core. WR sandwich composites exhibited highest fatigue strength and lowest stiffness degradation.
- Interfacial bond strength becomes weak at higher cycles and decreases the fatigue strength.
- Three failure modes have been observed: facesheet/core debonding, shear failure in the core and delamination. The first damage continues up to 75 % of fatigue life.
- Fatigue strength and failure load of the sandwich specimens increased with increase in core density.
- Stiffness degradation increased with increase in fatigue frequency and decreased with increase in density of PU foam.
- Stages involved in ultimate failure are different in low density and high density sandwich composites. Crack is initiated near the core/facesheet interface in low density composites, but in high density composites, crack is initiated in the middle of the core.

---

# REFERENCES


[1] Daniel IM, Abot LA, "Fabrication, Testing and analysis of composite sandwich beams, Comp Science Technology"; 60, p- 2455-63, 2000.

[2] Triantafillou T.C. and Gibson L.J, "Minimum weight design of foam core sandwich panels for a given strength." Material science and engineering, Vol. 95, p-.55-62, 1987.

[3] Fabric S.M., Laurent C., Jean-yves C and Emanuelle C, "Mechanical properties of high density polyurethane foams: I Effect of the density." Composites Science and Technology, Vol. 66, p- 2700-2708. 2006.

[4] K. Kanny, H. Mahfuz, "Flexural fatigue characteristics of sandwich structures at different loading frequencies." Composite Structures, 67, p- 403-410, 2005.

[5] Nitin Kulkarni, Hassan Mahfuz, Shaik Jeelani, Leif A. Carlsson "Fatigue crack growth and life prediction of foam core sandwich composites under flexural loading." Composite Structures. Vol. 59, p- 499–505, 2003.

[6] M. Zabhihpoor, S. Adibnazari, R Moslemian, A Abedian, "Mechanisms of fatigue in Foam core sandwich composites with unsymmetrical carbon/glass facesheets." JRPC, 26 (17), p-1831-1842, 2007.

[7] Zenkert, D. and Backlund, J, "PVC Sandwich Core Materials-Mode I Fracture Toughness." Composite Science and Technology, 34, p-225–242, 1989.

[8] Lilley, J. and Noble, F. W, "Fatigue Crack Growth in Polyurethane Foam." Journal of Material Science, 16: p-1801–1808, 1989.

[9] Yau, S. S. and Mayer, G, "Fatigue Crack Propagation in Polycarbonate Foam." Materials Science and Engineering, 78, p-111–114, 1986.

[10] Zenkert, D, "PVC Sandwich Core Materials: Fracture under Mode II Loading and Mixed Mode Conditions." Materials Science and Engineering, A108, p- 233–240, 1989.

[11] J L Grenested, S Hallstorm, J Kuttenkeuler, "On cracks emanating from wedges in expanded PVC foam." Engineering Fracture Mechanics, Vol. 54 (4), p- 445-456, 1996.

[12] Shipsha, A., Burman, M. and Zenkert, D, "On Mode-I Fatigue Crack Growth in Foam Cores for Sandwich Structures and Materials." Doctoral Thesis, Royal Institute of Technology, Department of Aeronautics, Rep 2001-13, 103-116, 1997.

[13] M. Burman and D. Zenkert, "Fatigue of foam core sandwich beams-1: undamaged specimens." Int Journal of Fatigue, Vol. 19(7), p- 551-561, 1997.

[14] M. Burman and D. Zenkert, "Fatigue of foam core sandwich beams-2: undamaged specimens." Int Journal of Fatigue, Vol. 19(7), p- 563-578, 1997.

[15] R.A Shinoi, S D Clark and H G Allen, "Fatigue behavior of polymer composites sandwich beams." Journal of Composite materials, Vol. 29, p-2423-2445, 1995.

[16] Nitin Kulkarni, Hassan mahfuz, Shaik Jeelani and Leif A Carlson, "Fatigue failure mechanism and crack growth in foam core sandwich composites under flexural loading." JRPC, Vol. 23(1), 2004.

[17] R.S Thomson, M Z Shah Khan, A P Mouritz, "Shear properties of a sandwich composite containing defects." Composite Structures, 42, p- 107-118, 1998.

[18] S.C. Sharma, M. Krishna, H.N. Narasimha Murthy, M. Sathyamoorthy, and Debes Bhattacharya. "Fatigue Studies of Polyurethane Sandwich Structures." JMEPEG, Vol.13, p-637-641, 2004.

[19] O. Konur and FL Mathews, "Effect of the properties of the constituents on the fatigue performance of composites: a review." Composites, Vol.20, Number 4, July 1989.

[20] Johnson A.F. and Sims G.D, "Mechanical properties and design of sandwich materials." Composites, Vol.17, p.321-28, 1986.

[21] Carlsson L A, Sendlein LS, Merry SL, "Characterization of facesheet /core shear fracture of Composite Sandwich beams." Journal of Composite Materials, Vol. 25, 101-116, 1991.

[22] Poursartip A, Ashby M F, Beaumont PWR, "The fatigue

damage mechanics of a carbon fiber composite laminate; 1-Development of model." Compos Science Technology, Vol. 25, p-193-218, 1986.

[23] Zenkert D., "Strength of Sandwich Beams with Mid-Plane Debondings in the Core", Composite Structures, Vol. 15, p-279-299, 1990.

[24] A. El Mahi, M. Khawar Farooq, S. Sahraoui and A. Bezazi "Modelling the flexural behaviour of sandwich composite materials under cyclic fatigue." Materials and Design, vol. 25, p-199–208, 2004

[25] Muhammad Kharwar Farooq, Abderrahim El Mahi and Sohbi Sahraoui, "Analysis of flexural behavior of sandwich composites under fatigue." Journal of reinforced Plastics and Composites, Vol. 26, (17), p-1831-1842, 2007.

[26] Basir Shafiq, Amiclar Quispitupa, "Fatigue Characteristics of foam Core sandwich Composite." Int Journal of Fatigue, Vol. 28, 96-102, 2006.

[27] S.C Sharma, H.N.Narasimha Murthy, M.Krishna, "Interfacial studies of fatigue behavior of polyurethane sandwich composites." Journal of reinforced Plastics and Composites, Vol 23(8), p-893-903, 2004.

[28] Sharma S C, Krishna M and Narasimha Murthy H N, J of Mater Eng Perform, Vol. 15, p-306-311.2006.

[29] Judawisastara,H., Ivens.J,Verpoest,I. "The fatigue behavior and damage Development of 3D Woven Sandwich Composites." Composite Structures, Vol. 43, 35-45, 2005.

[30] Kim R Y, Fatigue strength in Composites, "In Engineering Materials Handbook." ASM International, Metals Park, OH, 839-845, 1987.

[31] L C Hollway, P R Head, "Advanced Polymer Composites and Polymers in the Civil Infrastructure." Elsevier Science, edition1, ISBN-13: 978-0080436616, 2001.

[32] Gibson, L.J. and Ashby, M.F, "Cellular Solids, Structure and Properties", 2nd edition, Cambridge University Press, Cambridge. 1999.