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Shear Property Failure Testing of Gasoline Engine Combustion Chamber Produced with Fique Fibre Reinforced Epoxy Resin Composite Material

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ABSTRACT

Composite materials has proven to provide a better option in automotive, aerospace and aviation design applications due to exceptional strength and great aesthetics. This study presents failure testing analysis of the Fique Fibre Reinforced Epoxy Resin (FFRE) with Solid works Software. The simulated results show that the FFRE has relative compressive strength, light weight and good quality finishing. Failures exhibited by FFRE in withstanding the effects of flame suggest that remediation is imperative.

1. Introduction

Combustion chamber is that part of an internal combustion engine where the mixture of air and fuel is burned at the right time. The pressure caused by the burning of air/fuel mixture applies direct force to the components within the combustion chamber. This force developed, applies to the top of the piston which converts the gas pressure to mechanical energy. The combustion chamber is majorly part of the cylinder head with piston crown. It is the indentation where the inlet/intake valves and exhaust valves reside, with some part of the spark plug in an SI engine. The combustion chamber affects flame propagation. In the past, besides aluminum, cast iron was used as material for cylinder head and in extension combustion chamber. Cast iron, while being resilient than aluminum, is harder to work and weighs more. Aluminum also dissipates heat faster than cast iron. Cast iron is cheap, simple, available, has longer life but are heavy in weight. While, Aluminum block is light in weight, cheap enough, high resistance to high performance, longer life but won't last too long before maintenance and very expensive. Maintenance often requires rebore or replate.

FIQUE FIBRE

Fique Fibre are natural fibres native to Colombia (Furcraea andina), grown mainly in the departments of Cauca, Narino, Santander, and Antioquia, generating an average of approximately 11,200 jobs per year (Mahesh, et al., 2020).

The production of this fiber is carried out mainly in other countries of the American continent, some of them being Brazil, Ecuador, Venezuela, Costa Rica, and the Antilles (Navacerrada, Diaz & Fernandez, 2014). The fibre consists of three components: cellulose, hemicelluloses and lignin. Where cellulose is the main component that confers resistance and stability to the cell walls of the plant (Gomez Hoyos, et al., 2012).

The fibre is extracted from the leaf by mechanical techniques and is used mainly in sack packages and ropes. In its manufacturing process it is possible to obtain various presentations, from short fibres to meshes of different weights and textures (Ganan & Mondragon, 2002).

FIQUE FIBRE TREATMENT

To improve the compatibility of the natural fique fibres with the matrix used in the different DEcomposite materials, which for the most part have been polymeric, different agents have been used through chemical treatments that have improved the homogenization characteristics, degree of crystallization, fibre-matrix adhesion and thermal stability of the fibre (Sood & Dwivedi, 2018)

The main treatments found in the literature applied to fique fibre are listed below. However, its application (quantity of substance, additional additives, impregnation time, drying time) is modified according to the objectives of the research which leads to variations in application of them.

1. Thermal modification: the fibres are heated for a period of 30min to 12houres at a temperature that varies between 120ºC to 203ºC. Arjona et al. (2001) placed the fique fibre to dry at 105oC for 1hour, until obtaining complete loss of the water presented by the fibre, which improved its adhesion when the composites were manufactured.
2. Mercerization treatment: Mercerization is a treatment where alkaline substance is used to break the hydrogen bonds present in the chemical structure of the fibre, it consists of heating the fibre in a solution of NaOH, KOH, or LiOH (its percentage varies according to study) for a set period of time, drying is done at room temperature or in an oven. Castro et al. (2007) treated the fique fibre with NaOH for 10, 30, 60, 90, 120 and 300 minutes with concentrations of 2.5%, 3.7% and 5.0% and drying at 25ºC (room temperature) for 72hours and in an oven at 100ºC for 20hours. Obtaining that the mechanical properties of the fibre increased in greater proportion using 5% NaOH, and an exposure time of 30minutes with either of the two drying methods.
3. Treatment with silane: The fibres are immersed in a solution of water and alcohol with a silane base (SiH4) for a certain period of time, then the fibres were washed and dried at room temperature or in an oven. Munoz et al. (2018) treated the fique fibre with a silane coupling agent; immersing them for 1hour in a water-methanol solution, at a 50/50 v/v ratio, in which 1% and 0.5% of silane and di-cumyl peroxide were dispersed (percentage by weight with respect to the fibre), respectively. The pH of the solution was adjusted to 3.5and stirred for 30mins. The fibres were dried at 60ºC for 24hours, to finally be cured for 2hours at 120ºC.
4. Isocyanate treatment: Isocyanate is a compound that contains the isocyanate functional group –N=C=0. Treatment is typically carried out by immersing the fibre in this agent at intermediate temperatures for a set period of time. Ganan and Mondragon (2005) applied this treatment to the fique fibres using methylene diphenyl diisocyanate at a temperature of 70± 10ºC.
5. Esterification treatment: the fibres are immersed in a maleic anhydride solution. Ganan and Mondragon (2005) applied this treatment to the fique fibre by immersing it in maleic anhydride agent together with acetone, at a temperature of 55ºC ± 5ºC, then they were washed with acetone and left to dry 2hours at a temperature of 105ºC± 5ºC.

2. Materials and Methods

2.1 Fique Fibre Extraction and Treatment

Fique fibres were mechanically extracted from the plant stem by using electrically powered decorticating machine which expels the cortex and thereafter the fibres were neatly extracted. The employment of natural fibres as reinforcement material in composites is normally disadvantaged with the challenge of de-lamination and low mechanical properties. This is as a result of the highly hydrophilic nature of biofibres which transforms to poor interfacial bonding (Weng, 2004; Imoisili *et al.*, 2017). Hence, modification techniques of Mercerization and Acetylation were adopted to enhance effective interfacial bonding between the fibre and matrix.

In agreement with the works of Ihueze and Okafor (2014) and Obuka and Ihueze (2021), the fibers were soaked in a 0.4M NaOH solution for two and half (2.5) hours. The fibers were further treated with a 0.8 molar solution of $NaOCl_2$. By soaking in glacial acetic acid and further submerged for five (5) minutes in acetic anhydride containing a drop of Sulfuric acid (Mishra et al., 2003), the fibres were thereafter washed with water, dried in air, and finally oven dried at 80ºC.

2.2 Determination of Fibre Properties

Experiment and test on alkaline treatment with 0.5M concentration of NaOH was established as the best for treating plantain fibres (Obuka & Ihueze, 2021). Based on this finding the research goes on to determine the best soaking time suitable for the material of study at the established concentration. In carrying out this experiment four soaking times of 60mins, 105mins, 150mins, and 195mins were adopted. After these treatments of NaOH at above stipulated times, the fibres were washed with water to an approximate pH level of 7 and treated immediately with 1% concentration of acetic acid solution for 1hour, washed again as before (pH7) to remove any excess acid on the fibre surface. The treated fibres were then partially dried under the sun and finally oven dried at 80^0C. This was done to aim an approximate 0% moisture content (constant mass).

To determine whether the above stated procedure is ideal, some of the fibres were soaked at 60mins and 195mins soaking time and immediately transferred into acetic acid solution for 1hour without washing out excess NaOH on the surface. These were also washed with water and dried, as in the previous procedure but not in between treatments. This experiment on the optimum soaking time in alkaline solution was set-up as shown in Fig. 1.1.

Fig. 1.1: Experiment Set-up for Determining Soaking Time

Single strands of the fique fibres obtained from these treatments were tested for tensile strength to establish the best soaking time and treatment procedure. Results obtained from the tensile tests were captured in Table 3.3

2.3 Development of Fibre-Matrix Composite

The material under this research work is a composite comprising of Epoxy matrix and Fique (particulate) fibres. The production or compounding of the composite was carried out through injection molding process strictly adhering to the experimental design layout in the variation of machine parameters, and volume fraction mixing of the three particle sizes of the fibre (particulate). The process of impregnating the epoxy with fique fibres through injection molding was carried out with an injection molding machine at Akanu Ibiam Federal Polytechnic, Unwana, Ebonyi State.

Three particulate sizes of 0.5 mm, 1.0 mm and 2.0 mm where produced and designated as particle sizes 1, 2, and 3 respectively. Two coupling agents or compatibilizers were used in mixing the matrix and the fibre in order to evaluate their effects on the properties of the composite materials. These composites containing compatibilizers were designated as compatibilizer 01 and 02, while those composite materials formed without any compatibilizer were designated as control. These compatibilizers are both graphted polyethylene maleic anhydrides but of different chemical formula. Calculations of volume fraction of fique fiber was achieved following the derivations from rule of mixtures based on the procedures of Jones (1998), Barbero (1998) and implementation of Archimedes procedures in the determination of volume of fiber. Archimedes principle was used to determine the density of fibres from where the mass of both fibres and resin for particular volume fraction was evaluated.

The volume fraction of fibres (V_{fr}) which is the ratio of fibres to the volume of composites (V_c) and the weight fraction of fibre (W_{fr}) which is the ratio of the weight of the weight of composites (W_c) are two important composites variables that determine the properties of fiber reinforced composites. These two variables can be expressed as (Ihueze and Okafor, 2014)

$$V_{fr} = \frac{V_f}{V_f + V_r} = \frac{V_f}{V_c} \quad (1)$$

and

$$W_{fr} = \frac{W_f}{W_c} \quad (2)$$

$$= \frac{\rho_f V_f}{\rho_c V_c} = \frac{\rho_f}{\rho_c} V_{fr} \quad (3)$$

The properties of composites is greatly dependent on the volume fraction of fibres V_{fr}, so that the density of composite ρ_c, can be expressed as

$$\rho_c = \rho_f V_{fr} + \rho_r V_{frr} \quad = \rho_f V_{fr} + \rho_r (1 - V_{fr}) \quad (4)$$

The masses of fibre and resin are dependent on the mass or weight fractionW_{fr}, so that by expressing the mass of sample as

$$M_c = \rho_c V_c \quad (5)$$

where V_c, is the volume of sample usually estimated based on ASTM standard for a particular test, the mass of fibre can be estimated using the relation

$$M_f = W_{fr} \rho_c V_c \quad (6)$$

$$M_r = M_c - M_f \quad (7)$$

2.3.1 Mold Design and Specifications

The choices of moulds designed for this research are based on the mechanical properties of the developed materials that are subjects of investigation. These include tensile properties and flexural strength. Molds were therefore designed in accordance with ASTM D638, and ASTM D790 specifications

respectively. These molds are made of steel with reasonable thermal strength and thickness. On design for injection quantities of fibres and resin (Matrix), the weight fraction of fibres, volume fraction of fibres and estimated density of composite were used to estimate the mass of fibre and mass of resin necessary for each experiment according to a known ASTM standard size specification for a particular sample at a given response. Three volume fractions and three particle sizes were considered.

2.4 Strength Properties of the Figue Fibre Reinforced Epoxy (FFRE) Composite

Properties of developed composites were determined for various samples of different fique fibre-epoxy matrix volume fractions in line with set objectives. Accordingly, tensile and flexural properties were determined following laid down experimental procedures for tensile testing machine (TQ SM1000) and Beam apparatus (TQ SM1004). Composite design was carried out using standard specifications of ASTM D638 and D790 for tensile and flexural samples tests respectively.

3. Results and Discussion

Table 3.1 shows the computed masses of fibre and resin (matrix) for one sample of each response applying equations 1 through 7, while Table 3.2 shows the computed masses of fibre and resin that will be placed in the hopper at each injection run. In these tables M_f is mass of fibre in grams, M_r is mass of resin in grams, M_c is mass of composite (fibre and resin), and M_{in} is the total mass of fibre and resin in the hopper for a particular response at a particular volume fraction at a particle size plus the % allowance.

Table 3.1: Computed masses of fibre and resin at various responses

RESPONSE	**V_{fr}**	**ρ_c(g/cm^3)**	**M_c (g)**	**W_{fr}**	**M_f (g)**	**M_r (g)**
Flexural	0.1	0.8862	16.24936	0.014895	0.242035	16.00733
	0.3	0.7186	13.17625	0.055107	0.726106	12.45014
	0.5	0.551	10.10314	0.119782	1.210176	8.89296
Tensile	0.1	0.8862	8.124682	0.014895	0.121018	8.003664
	0.3	0.7186	6.588125	0.055107	0.363053	6.225072
	0.5	0.551	5.051568	0.119782	0.605088	4.44648

Table 3.2: Computed masses of fibre and resin at each injection run

RESPONSE/CAVITIES	**V_{fr}**	**M_f (g)**	**M_r (g)**	**M_c (g)**	**M_{in} (g)**
Tensile (6 cavities)	0.1	5.80884	384.17592	389.98476	519.97968
	0.3	17.42654	298.80336	316.22990	421.639872
	0.5	29.04422	213.43104	242.47526	323.300352
Flexural (4 cavities)	0.1	4.356648	288.13190	292.48855	389.984736
	0.3	13.06990	224.10259	237.17249	316.23000
	0.5	21.78317	160.07328	181.85645	242.475264

According to the L_{18} orthogonal array design of experiment, each of the samples at a particular test run is replicated 4 times, hence Figs. 2 and 3 depict the produced samples and their replicates for the two mechanical responses.

F *3.1*

Laboratory testing of developed composite materials.

The developed composite materials, Figue Fibre Reinforced Epoxy (**FFRE),** were subjected to two major mechanical responses of tensile and flexural tests at the Strength & Properties of Materials lab, A.I.F.P.U.

Table 3.3: Tensile Strengths of Fibres @30^{O}C Temperature at Varying Acetic Anhydride Concentration

Replication	5%		10%		15%	
	Tensile Strength (MPa)	**Elongation @ Peak (mm)**	**Tensile Strength (MPa)**	**Elongation @ Peak (mm)**	**Tensile Strength (MPa)**	**Elongation @ Peak (mm)**
R1	567.875	1.087	469.850	2.825	996.077	3.875
R2	54.027	1.225	1029.934	2.350	830.118	2.550
R3	353.169	3.125	843.603	3.912	150.879	0.375
Mean	**325.024**	**1.812**	**781.129**	**3.029**	**659.025**	**2.267**

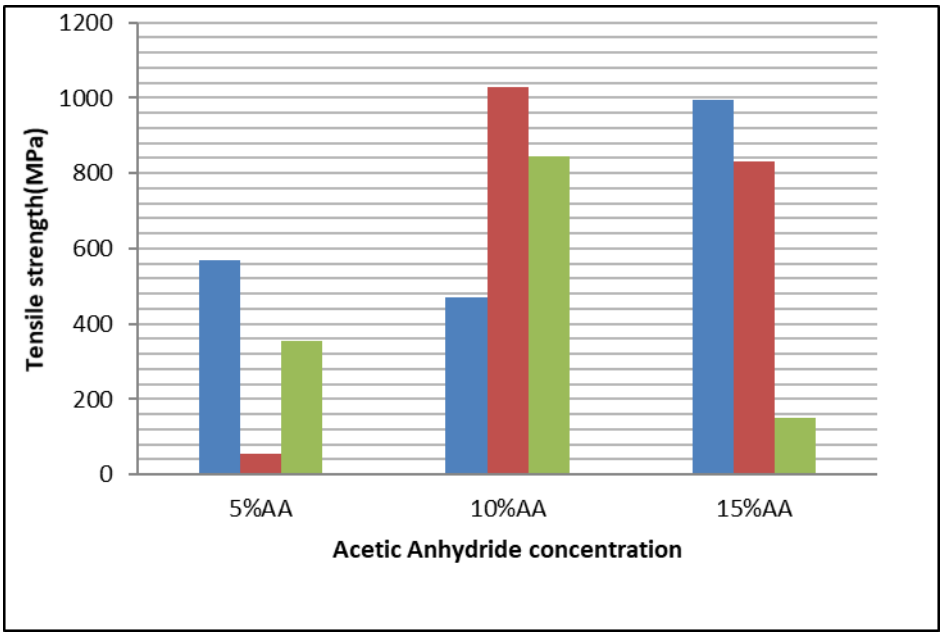


Fig. 1.4: Strengths at varying Acetic Anhydride concentrations at acetylation temperature 300C

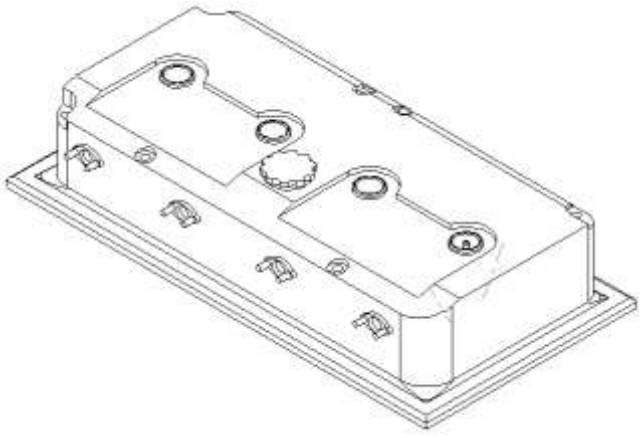
The test for strength conducted on the acetylated fibres indicates an optimum tensile strength of an average of 2,783 MPa for those fibres acetylated at 50^{0}C and at 10% acetic anhydride concentration. The results also show further increase in strength of about 272% when the fibre surface is further modified with acetic anhydride. Meanwhile, a treatment combination of 2% NaOH, 15% acetic anhydride at 50^{0}C and oven drying temperature of 80^{0}C is now the benchmark for the modification of the material development. These tests result and their analyses were meticulously carried out and clearly stated with the summarized analysis of the fibre development experiments which lead to the established optimal conditions for fibre material formation.

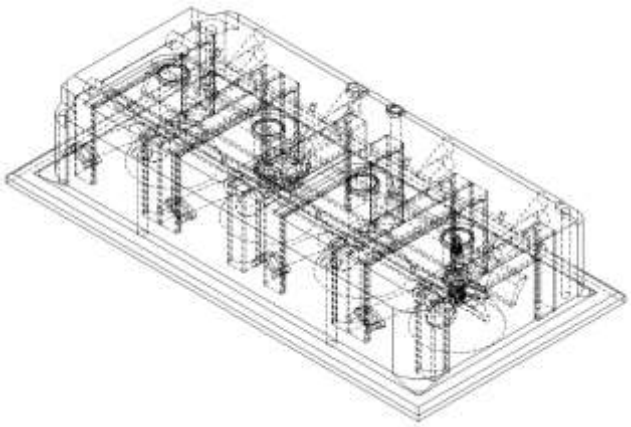
For an 15:85 ratio by weight of particulate fibre uniformly distributed within the epoxy resin and injected into moulds *(In situ epoxidation)* and cured at 30 deg. Celsius and 122 kPa (approximately 1.2 atm), families of similar stress vs Strain curves were obtained with optimum strength demonstrated by size 3 impregnated composite. Young's modulus and Ultimate Tensile Strength were seen to increase from E= 3.35 GPa (for a pure epoxy sample, n=7) to E=9.25 GPa; and UTS =86 MPa to 280 MPa. For an *l*750 mm by *b*20 mm by *d5 mm* test specimen of the composite, significant flexural strength *(flexural rigidity)* improvement of about 900% was recorded. These values are consistent with effective fibre treatment and modification methods adopted for the work

In addition to laboratory tests carried out to determine tensile, flexural and other functional properties of the composite material, its susceptibility to heat induced charring and ability to retain strength at high temperatures were ascertained via controlled firing in a research kiln. Upon firing of the samples of the composite material up-to 600^0C, significant structural and morphological distortions were observed. Unlike what is expected of thermosets, distortions where largely irrecoverable ostensibly due to the bio-fibre incrustations.

3.2 CAD Modeling of Cylinder Head

CAD model of the cylinder head, with four combustion chambers, for a typical gasoline engine is presented in figure 1.5. Dimensions are typical of that of Honda Accord 1999 model measuring 440mm x 200mm x 90mm for Length, Breadth, and Depth respectively. In carrying out the design, interaction of the developed composite material's properties with design objective for cylinder head was borne in mind. To be robust enough to resist mechanical and thermal stresses associated with normal operation of an Otto cycle 4-Stroke SI engine, features for constraining members were fortified while cross-sectional thicknesses across flow passages were modified to minimize possible turbulence.





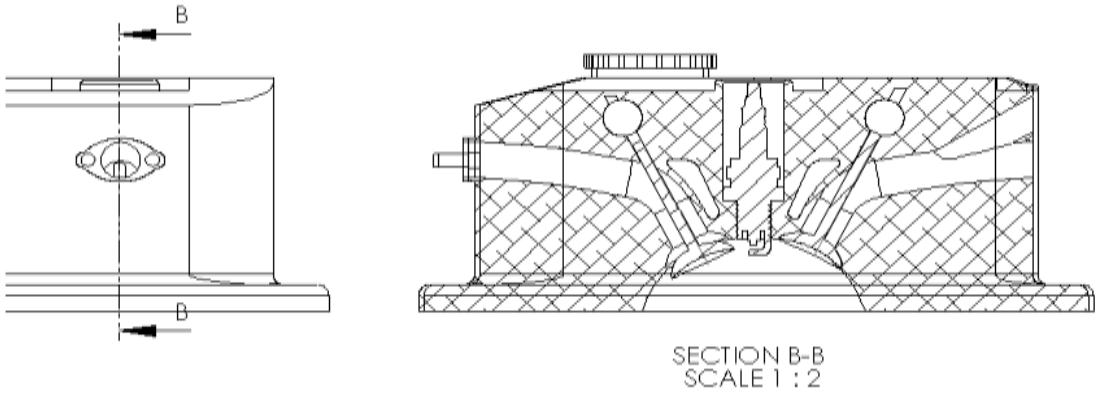


Fig. 1.5(a-e): Drawings of the Cylinder head with Combustion Chamber

SolidWorks software was used in the design and assembly components which make up the cylinder head.

3.3 Analysis of Deformation Resistivity

Prevalent failure modes that would arise based on sophisticated service conditions of typical S.I. engine are those likely to be induced by pressure and thermal loads. Failure on the account of other plausible phenomena like poor cooling and lubrication system failure would not be considered in the current analysis as they are much easier to be dealt with once mechanical strength, structural, and morphological stability of the materials of the cylinder head, block, and crankshaft assembly are guaranteed.

For the purpose of the current simulation of the designed cylinder head, synergistic effect of both the thermal and pressure loads is of engineering significance. This has become the case as both acts simultaneously. Emphasis is on distribution of stress, displacement (deformation), and strain on and around the combustion chamber. It has been variously reported (Humphrey *et al*, 2018, Rajput, 2011) that conditions of pressure and temperature at the end of each compression stroke in referenced models of gasoline (S.I.) engines are in the neighborhood of 8Bars and 300°C; and 35Bars and 600°C for diesel (C.I.) engines of similar size. Based on this, design details alongside material properties were captured in SolidWorks 2014® for the purpose of CAD simulation. Stated critical values of failure inducement determinants, temperature and pressure, were impressed with the aid of SW-Simulation add-in and values of stresses (N/m^2), displacements (deformations, mm) and strains were examined.

Table 1.5 summarizes the properties of the FFRE while figure 1.6 shows a Simulation-Advisor in which mesh size for Finite Element Analysis (FEA), fixturing type and locations, and other test conditions were specified. Figure 1.7(a-e) depicts results for stress distribution within the component based on combined pressure and thermal loading of 8x10^5 N/m^2 (8Bars) and 300°C, typical of operating values for the designed model; although simulation of effects of temperatures up-to 800°C were also studied.

Table 1.5: Material Properties (Figue Fibre Reinforced

Epoxy, FFRE)

Property	Value	Unit
Elastic Modulus in X	9250000000	N/m^2
Poisson's Ration in XY	0.32	N/A
Shear Modulus in XY		N/m^2
Mass Density	1450	kg/m^3
Tensile Strength in X	280000000	N/m^2
Compressive Strength in X	104000000	N/m^2
Yield Strength		N/m^2
Thermal Expansion Coefficient in X		/K
Thermal Conductivity in X	0.102	W/(m·K)
Specific Heat		J/(kg·K)
Material Damping Ratio		N/A

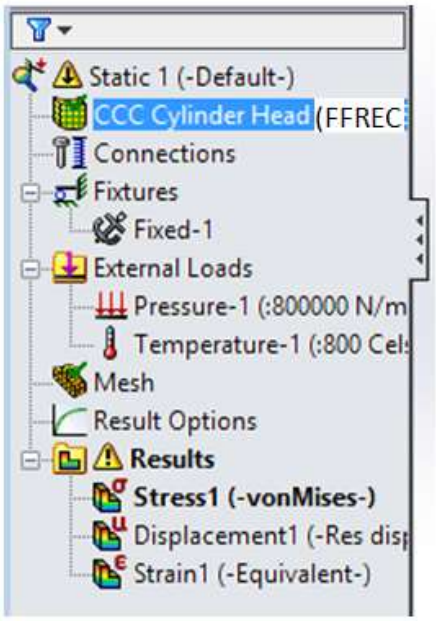


Fig.1.6: Simulation Advisor

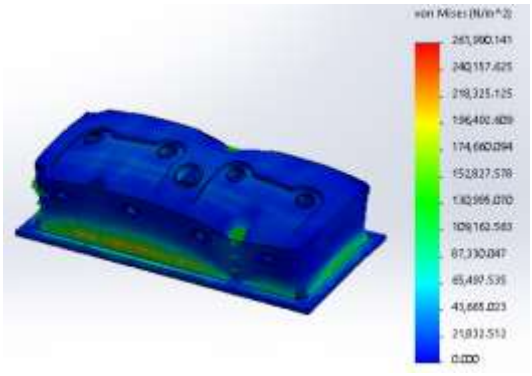


Fig. 1.7(a)

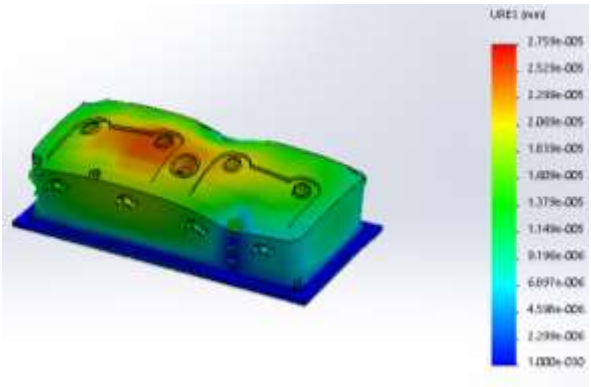


Fig. 1.7(b)

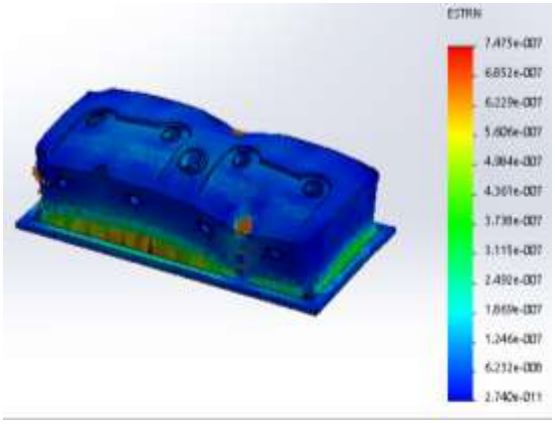


Fig. 1.7(c)

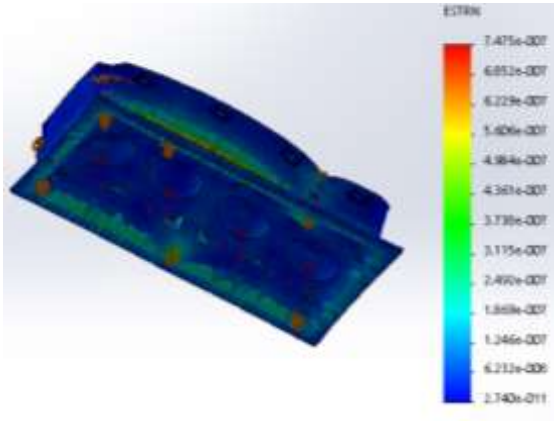


Fig. 1.7(d)

Fig.1.7(a-d): Combined temperature and pressure simulation result

Fig. 1.7(a), shows that maximum stress level suffered by the material on the account of combined loading is generally within acceptable limits. Deformation in terms of dimensional changes is reasonably low and thus is of no concern, but charring of the material, especially, at the combustion chamber is a factor that is of serious engineering significance as Fig. 1.7(b) indicates the possibility of material deterioration radiating outwards from flame sources. Fig. 1.7(c) and Fig. 1.7(d) represents different axonometric perspectives of the CAD model with the concomitant strains and regions most affected by stress. Strain values are consistent as depicted on the colour bars. Responses of combustion forces are felt mainly at remote regions as shown with maximum strain of about 0.00682. This value, although within allowable boundary, can be effectively mitigated by implementing a remediation scheme for the combustion chamber and its adjoining surfaces.

4. Conclusion

Based on the simulation results, FFRE composite is a candidate material for possible manufacture of integrated cylinder head with engineered remediation for the surfaces directly exposed to combustion flames. The material's relatively high compressive strength, light weightiness, alongside its poor thermal conductivity was veritable functional properties for the proposed application. However, its failure to withstand effects of combustion flames means that effective remediation must be invoked.

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