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DISTRIBUTION OF STRESSES IN A DOUBLE-LAP BONDED ASSEMBLY SUBJECTED TO IMPACT AND FIRE

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ABSTRACT

This work concerns the study of a double-lap bonded assembly subjected to an impact during its exposure to fire. Numerical simulations have been carried out using ABAQUS. They have shown that the most sensitive zone is the adhesive which shows an early deterioration. The adherent deteriorates less quickly but especially in the areas of the glue. Moreover, along the adhesive, the stress distribution shows a stress concentration at the edges and the average of these stresses along the length decreases as a function of the time of exposure to fire. These simulations have made it possible to investigate the evolution of stresses in the assembly subjected to fire and impact, as a function of the time of exposure to fire. This would assist designers in dimensioning bonded assemblies of composite parts in structures.

Keywords: bonded joints; Impact, fire exposition, numerical simulation.

INTRODUCTION

Nowadays composite materials are a particularly attractive alternative for the construction of naval structures. Insensitive to marine corrosion and seawater, they provide excellent buoyancy and enable the production of large and solid hollow volumes. Lightening structures is undoubtedly one of the main arguments for the use of these materials. Unfortunately a big disadvantage for composite materials is their flammability causing quick degradation of the material (A.P. Mouritz, 2006). Nevertheless, in many fire scenarios only the face exposed to flames burns and the formed char protects the inside of the material and the unburnt surfaces which proves to be great advantage. The characterization of their thermo-mechanical behavior when subject to a fire scenario is quite a delicate task since it varies widely from a material to another. Therefore it is first necessary to adopt a certain fire thermal model in order to gain accurate quantification of the temperature field variation as a function of time. It is also necessary to have good experimental data to understand behavior of composites in fire and to implement numerical models with input data. In this view, we study in parallel the evolution of the properties and the durability of the composites subjected to the high temperatures (TranVan et al., 2014; Legrand et al., 2015). Many fire thermal models were proposed based on the standard heat equation defining the heat conduction process, accompanied by additional terms describing other thermal, physical and chemical processes that are present during a fire scenario (A.P. Mouritz, 2006). The most important thermal models were provided by Pering et al (G.A. Pering, 1980), Henderson et al (J.B. Henderson, 1985), Gibson et al (A.G. Gibson, 1995) and Florio et al (J. Florio, 1991). Knowledge of the temperature

variation at different points of the specimen would then make it possible to determine the values of the required mechanical properties at each point and at any time of fire exposure. As for the mechanical loading since the dynamic impact load is common with adhesive bonded assemblies since adhesives, like most polymer materials, are sensitive to the rate of applied force. Therefore a dynamic test called the SHPB (B. Hopkinson, 1914) setup i.e. the split Hopkinson pressure bars, also named as Kolsky bars in some references, was considered.
As such in this work we studied the distribution of stresses in a double-lap bonded assembly subjected to impact, and fire. The analytical procedure employed envolves:

- Application of a fire heat flux to the modelled specimen in order to generate the through-thickness temperature variation in function of time.
- Evaluation of the mechanical properties at different points through the thickness.
- Mechanical modelling of the whole specimen subject to thermal and impact load.

MODEL DESCRIPTION

The double-lap bonded assembly is constructed of three glass/vinyl-ester composite plates bonded together using and epoxy resin as adhesive (Challita, 2009) as shown in Fig. 1 below.

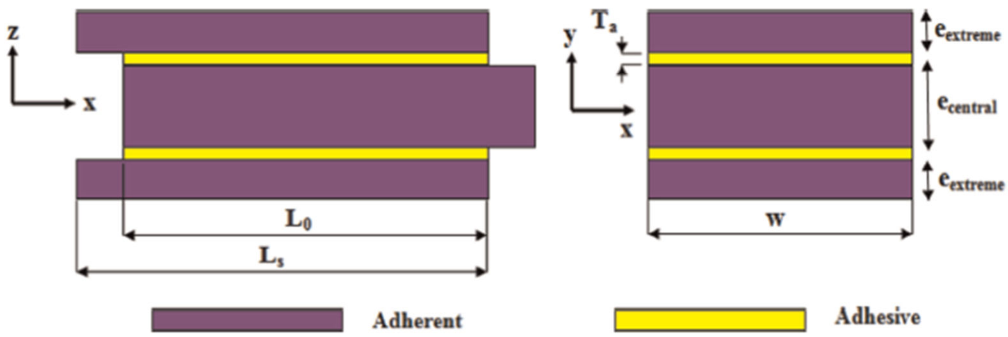

Fig. 1 - Double lap joint specimen

The element dimensions are:
L_0 = 14 mm
L_S = 16 mm
w = 12 mm
$e_{central}$ = 4 mm
$e_{extreme}$ = 2 mm
Ta = 0.1 mm.

The thermal and mechanical properties of the glass/vinyl-ester composite adherents are (Feih, 2007), (C.A.R.M.A, 2014):

vf: Volume fraction of fibres = 55%
Specific heat of glass = 760 $J.kg^{-1}.K^{-1}$
Specific heat of glass/vinyl-ester (45°C) = 960 $J.kg^{-1}.K^{-1}$
Specific heat of glass/vinyl-ester (140°C) = 1210 $J.kg^{-1}.K^{-1}$
Specific heat of glass/vinyl-ester (290°C) = 1360 $J.kg^{-1}.K^{-1}$

Density of vinyl-ester = 1140 kg.m^{-3}
Density of glass = 2560 kg.m-^{3}
Density of glass/vinyl-ester = 1921 kg.m^{-3}
Thermal conductivity of glass = 1.09 W.m^{-1}.K^{-1}
Thermal conductivity of vinyl-ester = 0.19 W.m^{-1}.K^{-1}
Thermal conductivity of glass/vinyl-ester in the direction of fibers = 0.685 W.m^{-1}.K^{-1}
Thermal conductivity of glass/vinyl-ester in the transversal direction = 0.4296 W.m^{-1}.K^{-1}
A: Pre-exponential factor of Arrhenius law = 5.59.10^{13} s^{-1}
E: Activation energy =2.12.10^{5} J.mol^{-1}
n: Order of decomposition reaction = 1
Qp: Heat of decomposition = 378800 J.kg^{-1}
Decomposition temperature = 350^{o}C
Young modulus of glass = 72 GPa
Young modulus of vinyl-ester (25 ^{o}C) = 4.15 GPa
Poisson ration of glass = 0.21
Poisson ration of vinylester (25 ^{o}C) = 0.37

The thermal and mechanical properties of the epoxy adhesive are (C.A.R.M.A, 2014), (Chiguma, 2013):

Specific heat = 1000 J.kg^{-1}.K^{-1}
Thermal conductivity = 1.6 W.m^{-1}.K^{-1}
Density = 2300 kg.m^{-3}
Young modulus (25 ^{o}C) = 1000 MPa
Poisson ration (25 ^{o}C) = 0.4

FIRE THERMAL MATHEMATICAL MODEL

The Gibson et al fire thermal model (Gibson, 1995) was chosen to simulate the fire scenario in hand since no carbon/fiber reaction will take place under the applied heat flux of 25 kW/m2. A second reason for its adoption is the implementation easiness and the results accuracy achieved through previous research (Feih, 2007), (Dodds, 2000), (Davies, 2006). This model includes three of the most important thermal phenomena, which are heat conduction, polymer matrix pyrolysis, and diffusion of decomposition gases. The heat conduction process is present in almost all fire scenarios. The two other processes appear in general when the matrix decomposition process initiates, at temperatures ranging from 250 to 400°C, depending on the material. The mathematical equation of the Gibson et al fire thermal model is (Gibson, 1995):

$$\rho C_p \frac{dT}{dt} = \frac{d}{dx}\left[k_x \frac{dT}{dx}\right] - \dot{m}_g \frac{dh_g}{dx} - \frac{d\rho}{dt}.\left(Q_p + h_c - h_g\right) \quad (1)$$

In Eq. (1) x indicates the through thickness direction. On the right side of the equation, the three terms are related to heat conduction, polymer matrix pyrolysis and gas convection respectively. The enthalpies of the solid material and gas are:

$$h_c = \int_{T_0}^{T} C_p dT \quad (2)$$

$$h_g = \int_{T_0}^{T} C_{pg} dT \tag{3}$$

Polymer matrix decomposition induces variation of density throughout the specimen. The most accurate estimation of this change in density derives from the Arrhenius decomposition kinetics and is calculated by (Mouritz, 2009):

$$\frac{d\rho}{dt} = -(\rho_0 - \rho_\infty)\left[\frac{\rho - \rho_\infty}{\rho_0 - \rho_\infty}\right]^n A.exp\left(\frac{-E}{R.T}\right) \tag{4}$$

Where A, n, and E are kinetic parameters found through thermogravimetric analysis (TGA). The mass flow rate of pyrolysis gases can be calculated from the continuity equation by (Henderson, 1985):

$$\frac{d\dot{m}_g}{dx} = -\frac{d\rho}{dt} \tag{5}$$

The polymer matrix pyrolysis and gas convection terms of Eq. 1 were added to the pre-defined 3D standard heat equation of ABAQUS software using DFLUX subroutine written in the Fortran language (Rizk, 2014).

FIRE THERMAL SIMULATION

The double lap bonded assembly was modeled in ABAQUS software. The constitutive elements were defined as solid parts associated with their relevant thermo-mechanical properties and joint together using tie constraints. An adequate mesh of DC3D8 elements (Abaqus, 2012) was then applied to each part as shown in Fig. 2.

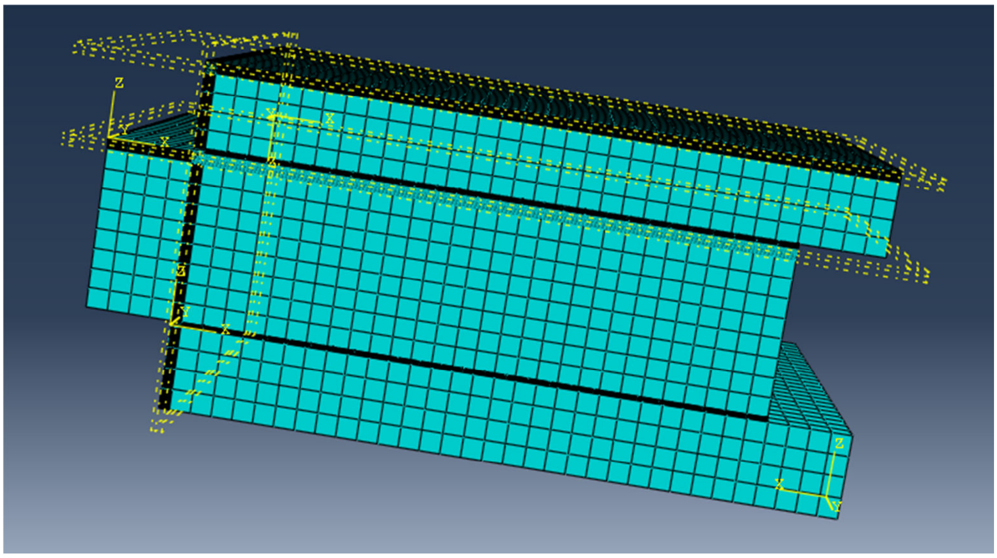

Fig. 2 - Specimen overall mesh

The mesh was refined at the edges, at the areas subject to the applied heat flux where the most important changes in temperature are predicted. A heat flux of 25 kW/m^2 was then applied to the top surface of the assembly, simulating the actual fire case as shown in Fig. 3.

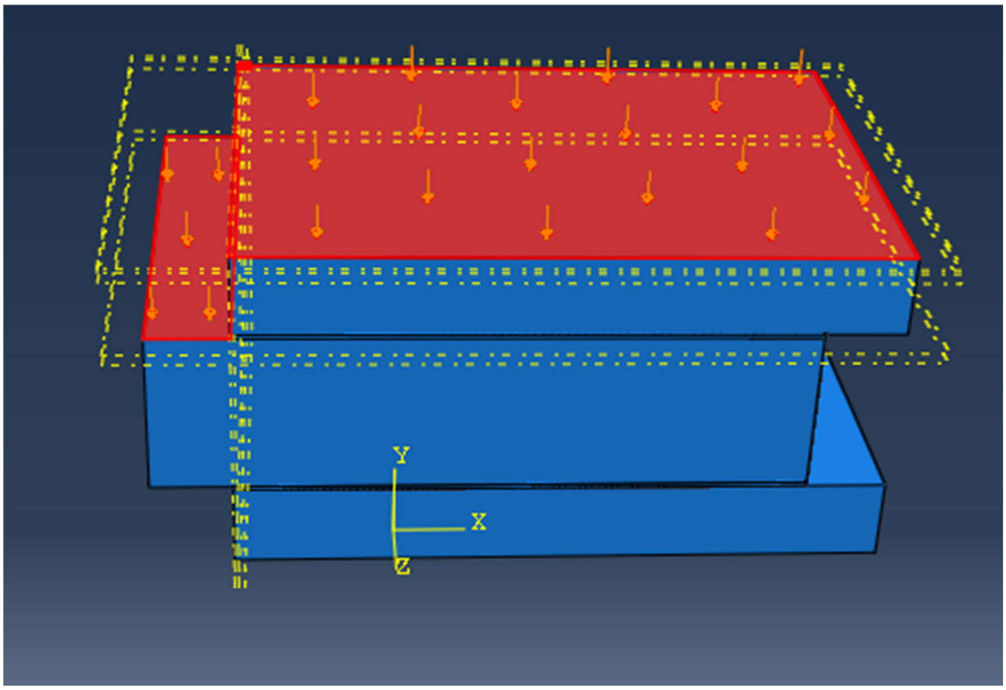

Fig. 3 - Assembly model and applied heat flux

The thermal interaction of the whole assembly with the external environment was defined by boundary conditions taking into consideration the convective and radiative heat fluxes. A user defined body heat flux was also added to include the polymer matrix pyrolysis and gas convection terms as per the Gibson et al fire thermal model (Gibson, 1995). As such a personalized DFLUX subroutine (Abaqus, 2012) written in the Fortran language was required. The heat transfer analysis was then initiated, generating the variation of the temperature field throughout the whole assembly as a function of time. Temperature variations as a function of time were then extracted at 13 different points in the through-thickness direction, which serves as input data for the quantification of the mechanical properties and the mechanical impact model. Fig. 4 presents the selected points. Fig. 5 presents the extracted results at each of these points.

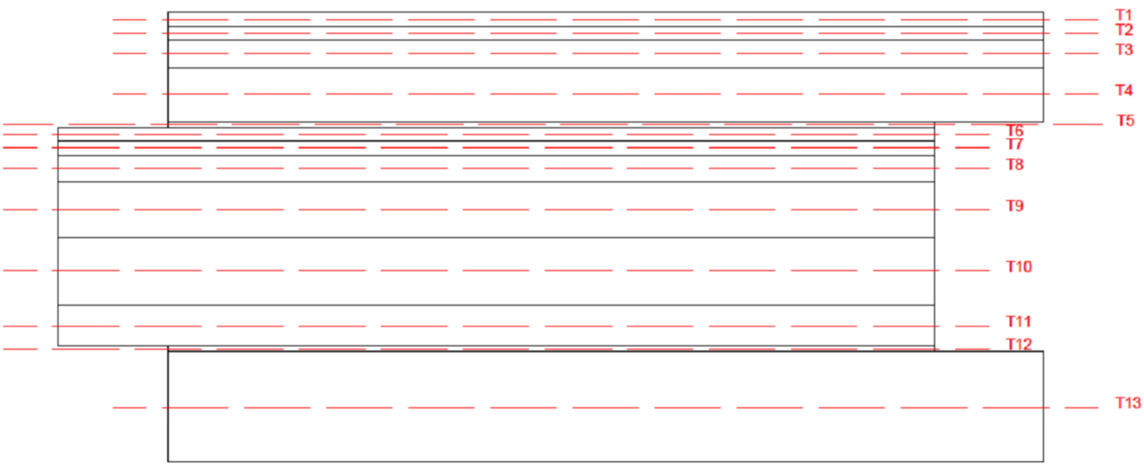

Fig. 4 - Through-thickness temperature extraction points

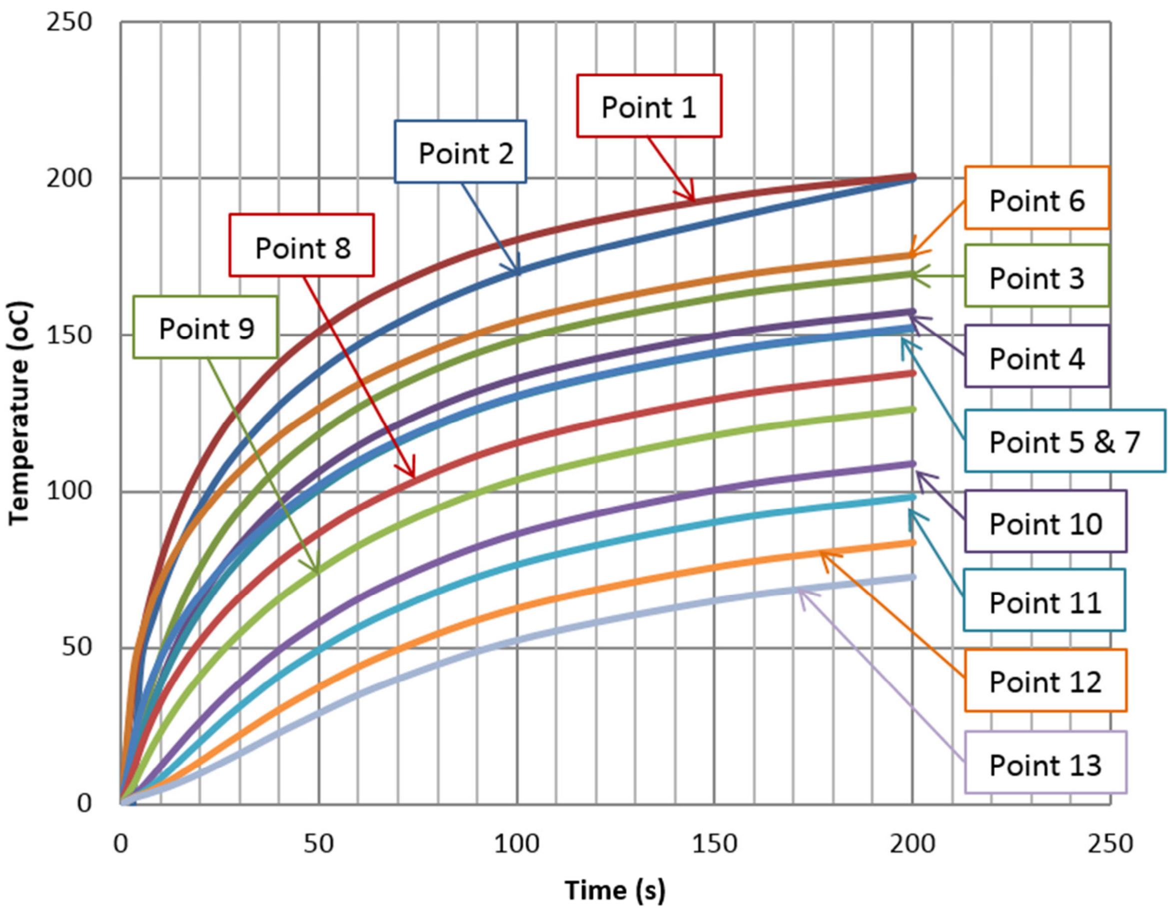

Fig. 5 - Temperature variations in the through-thickness direction

With this data in hand it was then possible to generate the variation of the mechanical properties at each depth in the through thickness direction and for each of the materials, serving ultimately as input for the mechanical impact model of the specimen when subject to fire.

MECHANICAL IMPACT MODEL

The SHPB (Split Hopkinson Pressure Bar) Test (Hopkinson, 1914) was adopted in order to characterize the dynamic behavior of the material subject to impact loading. In the test the assembly is sandwiched between two elastic long bars made of the same steel as shown in Fig. 6.

One bar is the input bar i.e. incident, the other is the output bar i.e. transmitter. A third bar, called the projectile i.e. striker, will hit the unconstrained end of the input bar, hence generating the compressive wave in the input bar. At the interface input bar/sample, only one part of this wave will be transmitted from the input bar to the sample, ε_{tra}, after the other part is reflected in the input bar, ε_{ref}. Then, gages cemented on the input bar will record the incident and reflected waves, and on the output bar, gages will measure the transmitted wave. These three waves will be processed in order to establish the behavior of the tested specimen

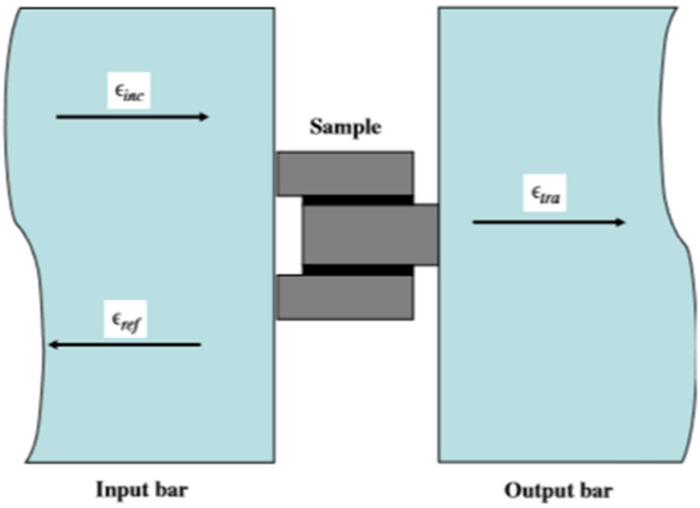

Fig. 6 - SHPB test schematic

In this study the interest is the shear stress in the adhesive as such average shear stress in the adhesive layer should be computed using the below formula:

$$\tau_{xy}^{av}(t) = \frac{1}{L_0 \times T_a \times W} \iiint_{0\,0\,0}^{L_0\,W\,T_a} \tau_{xy}(x, y, z, t)dxdydz \tag{6}$$

The shear stress being constant in the direction of the width, from previous studies (Hazimeh, 2015), values can be extracted at the vertical plane defined by (y=w/2) which serves also as one of the two planes of symmetry of the sample, the vertical one.

Thus,

$$\tau_{xy}^{av}(t) \approx \frac{1}{L_0 \times T_a} \iint_{0\,0}^{L_0\,T_a} \tau_{xy}\left(x, y = \frac{w}{2}, z, t\right) dxdz \tag{7}$$

Assuming further the stress to be constant in the direction of the thickness:

$$\tau_{xy}^{av}(t) = \frac{1}{L_0} \int_0^{L_0} \tau_{xy}\left(x, y = \frac{w}{2}, z = \frac{T_a}{2}, t\right) dx \tag{8}$$

MECHANICAL IMPACT SIMULATION

The first step into the initiation of the mechanical simulation is the characterization of the mechanical properties of the material.

Previous studies have shown the results of an impact on a double lap joint having constant mechanical properties (Saleh, 2014). In this study the variation of the mechanical properties as a function of temperature was taken into consideration.

The variation of Young modulus as a function of temperature for a majority of polymers is a major parameter in studies involving thermo-mechanical loading as this modulus drops suddenly at a certain temperature called the material transition temperature (Mouritz, 2006), (Hugh, 2004). For example, Young modulus of vinyl ester drops fast at around 100°C (Mouritz, 2006). This implies that above the transition temperature the whole structure experiences major fragility due to the mechanical deterioration of its constituents, especially those of polymeric nature such as vinyl-ester and epoxy.

Young modulus variations as a function of temperature were acquired for vinyl-ester (Mouritz, 2006) and epoxy (Hugh, 2004) resins and were used to calculate the overall mechanical properties of glass/vinyl-ester composites and their variation with temperature, using the mixture laws for composites (Bertherlot, 1999), (Nettles, 1994).

The whole solid was then modeled as 13 layers where each one was associated with its relevant material and temperature variations extracted from the fire thermal simulation. The layers were joint together using the tie constraints feature of ABAQUS. Fig. 7 shows the laying configuration.

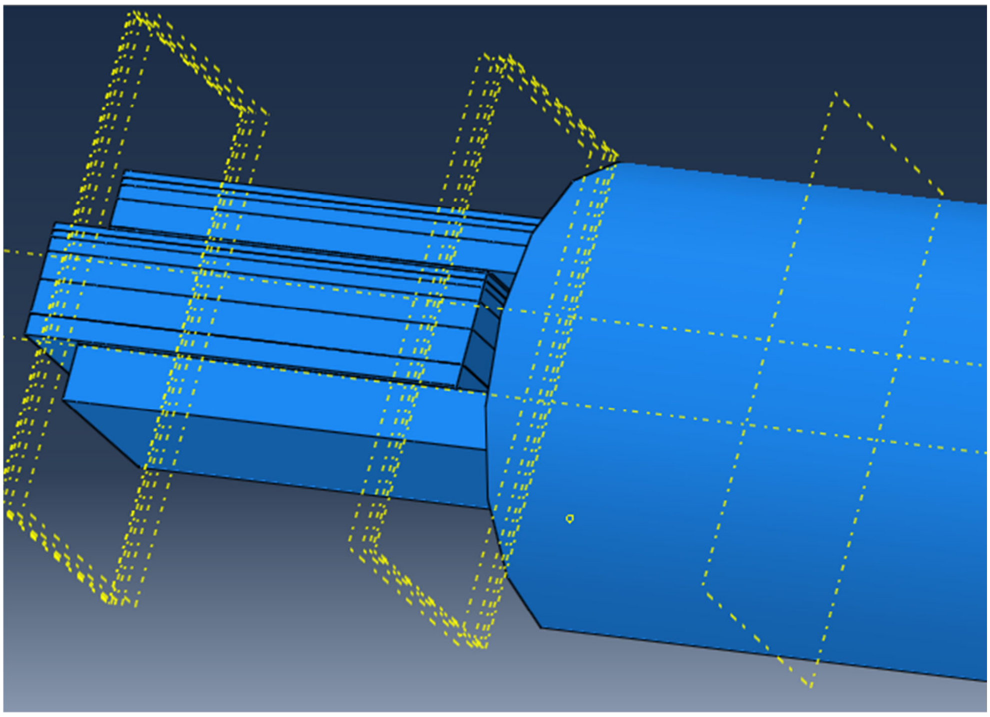

Fig. 7 - Numerical model formed by 13 tied layers

The mechanical impact model consists of studying the mechanical response for the structure at specific times during exposure to fire. It was therefore necessary to calculate the material properties accordingly. Table. 1 presents the calculated mechanical properties of the first layer at different fire exposure times. Similar tables were also generated for the other layers.

A C3D8 linear explicit mesh was then applied and refined in order to obtain optimal results. The main objective was then to simulate an SHPB impact test (Hopkinson, 1914). A metallic bar was added to the model on the opposite side of the impact in order to have reliable results of the test. The impact is applied on the central adherent in the x longitudinal direction. Fig. 8 shows the specimen and the applied impact load as modeled in ABAQUS. The amplitude of the impact load is presented in Fig. 9

Mechanical impact simulations were conducted for five different fire exposure times: t=0s, t=19s, t=29s, t =44s, and t=200s.

Table. 1 - Mechanical properties in MPa of layer 1 at several times of fire exposure.
(With ve = vinyl-ester and vve = glass/vinyl-ester).

Time (s)	**T1 (^{o}C)**	**Eve**	**Evve**	**Gve**	**Gvve**	**Etvve**	**F=Gtvve**
0	0	4223	43150	1564	3272	8779	2727
3	45	4158	43121	1540	3225	8654	2687
5	59	4224	43151	1564	3273	8782	2727
8	76	4348	43206	1610	3363	9022	2803
12	94	2160	42222	800	1723	4636	1436
19	113	222	41350	82	182	492	152
29	133	84	41288	31	69	186	57
44	152	66	41280	24	54	146	45
67	171	49	41272	18	41	110	34
101	187	35	41266	13	29	77	24
152	200	23	41260	9	19	52	16
200	206	17	41258	6	14	38	12

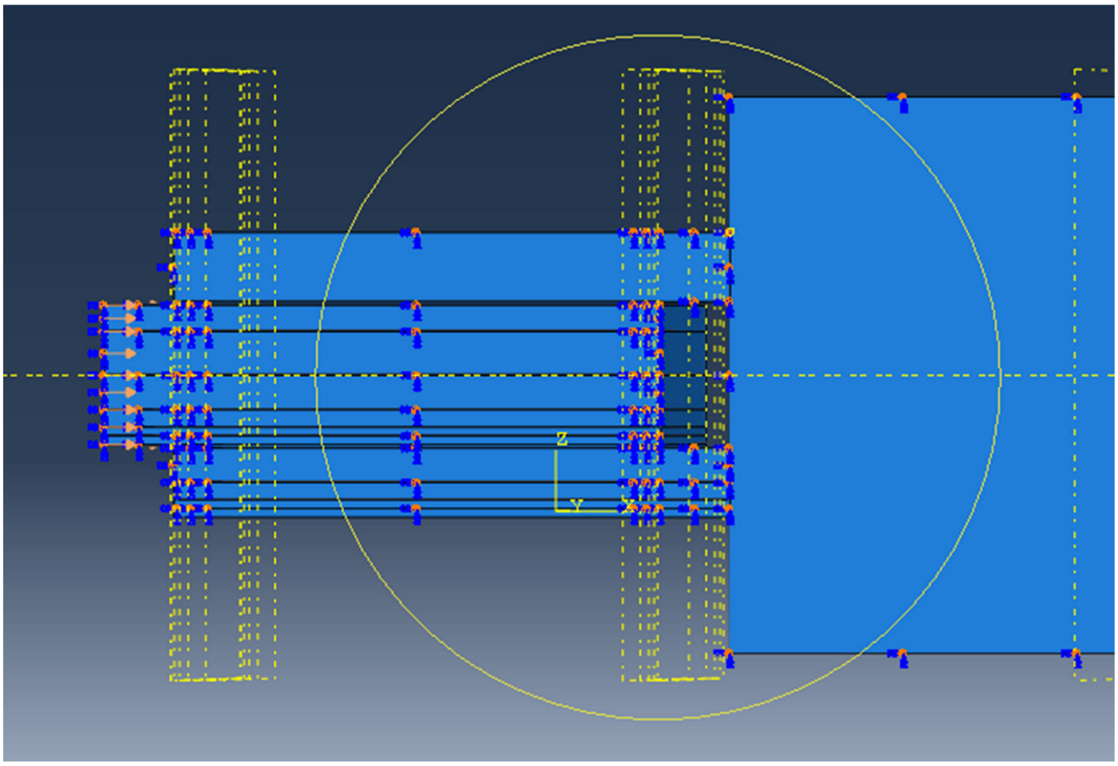

Fig. 8 - The mechanical model in ABAQUS

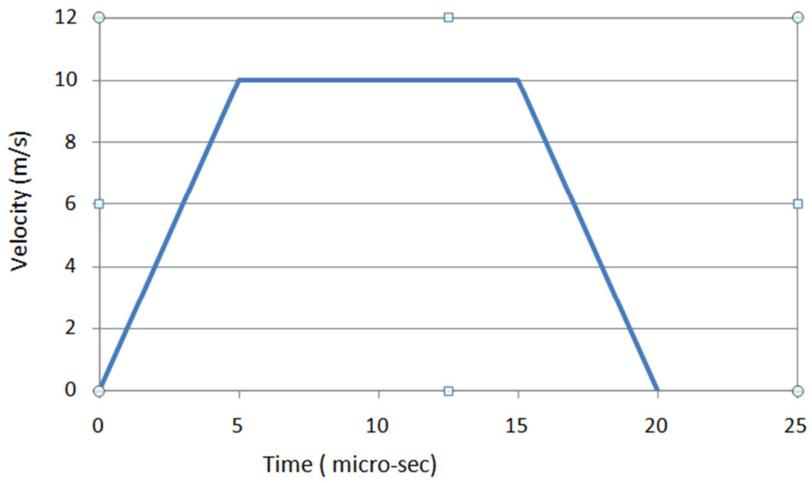

Fig. 9 - Amplitude of the impact load

RESULTS

Transient mechanical simulations were performed for each of the selected times of exposure for an overall duration of 40 micro-seconds and the stress distribution field was then extracted. Fig.10 is a sample of this physical quantity at t=19s.
It is obvious that the weakest points in the adherents are in the areas highly exposed to fire and adjacent to the adhesive. Fig. 11 is an enlarged presentation of that area.

Shear stress values were then obtained from each of the simulations along an horizontal section through the upper adhesive layer that is close to the fire heat flux as shown in Fig. 12 The extracted results are presented in Fig. 13.

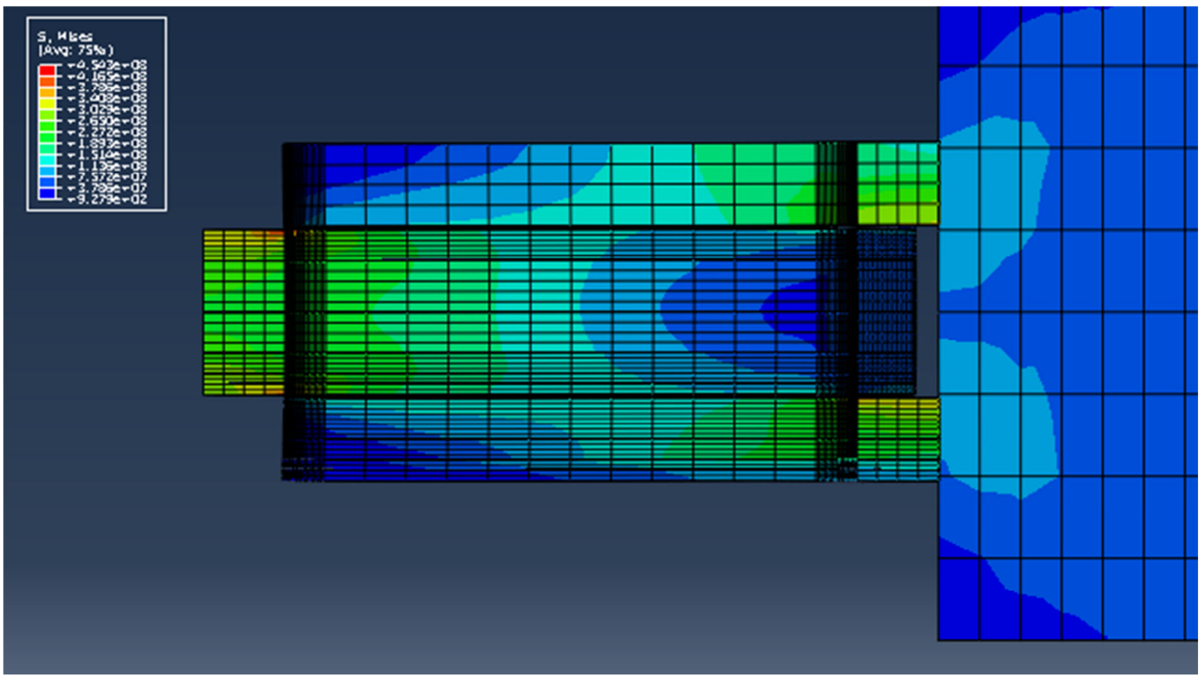

Fig. 10 - Von Mises stress distribution for simulation at t=19s

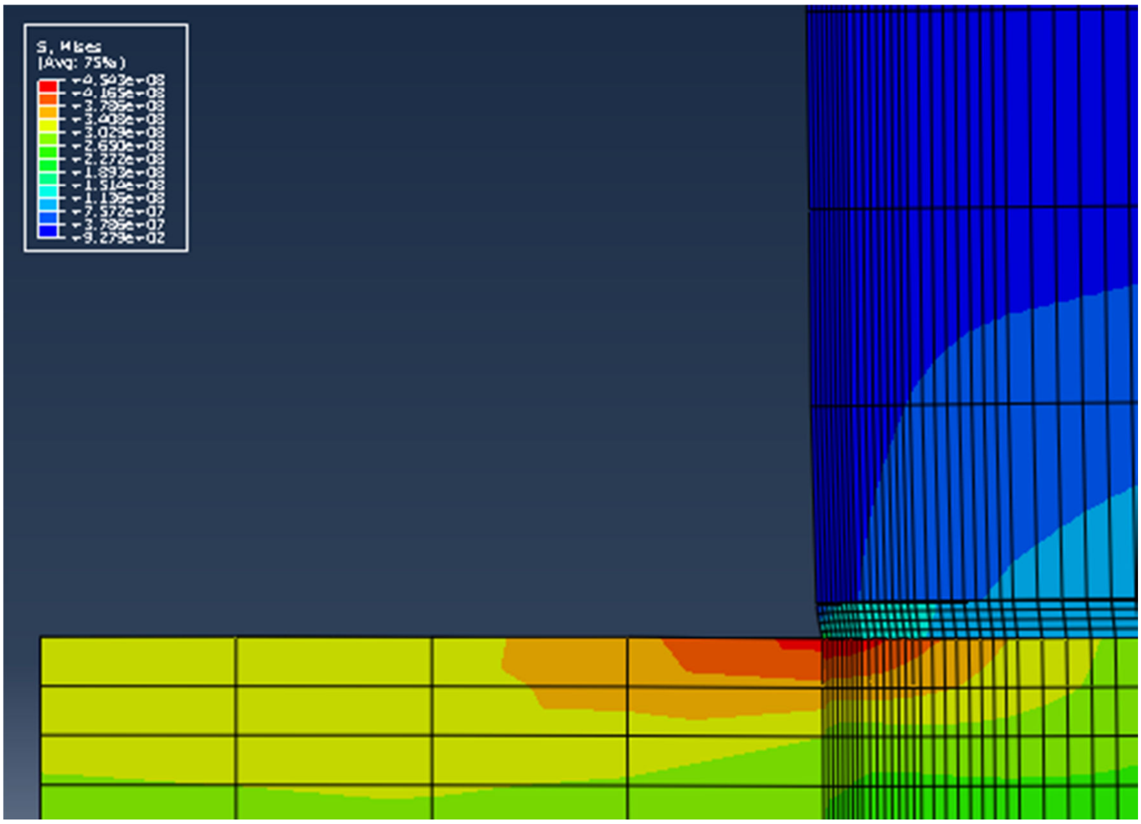

Fig. 11 - Weak point of the adherent

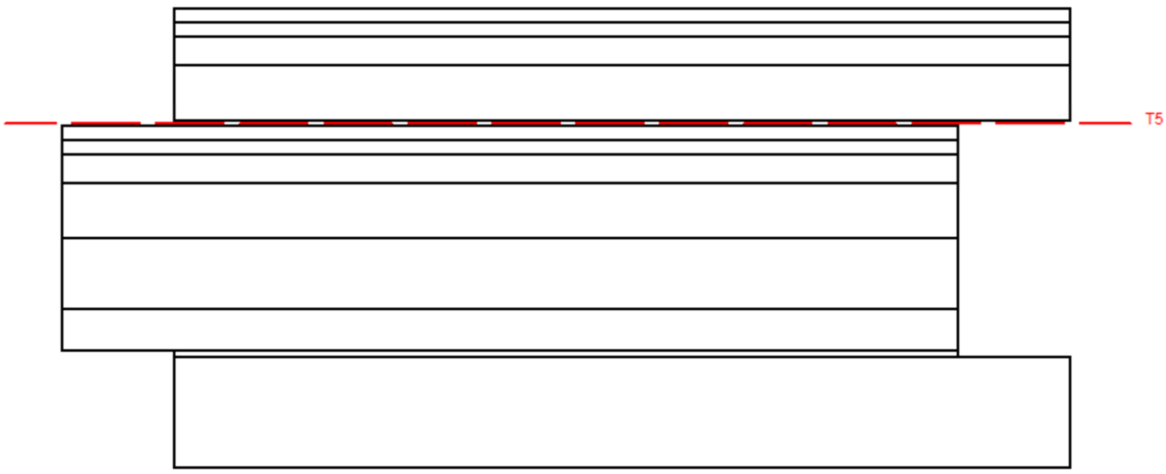

Fig. 12 - Horizontal section for data extraction

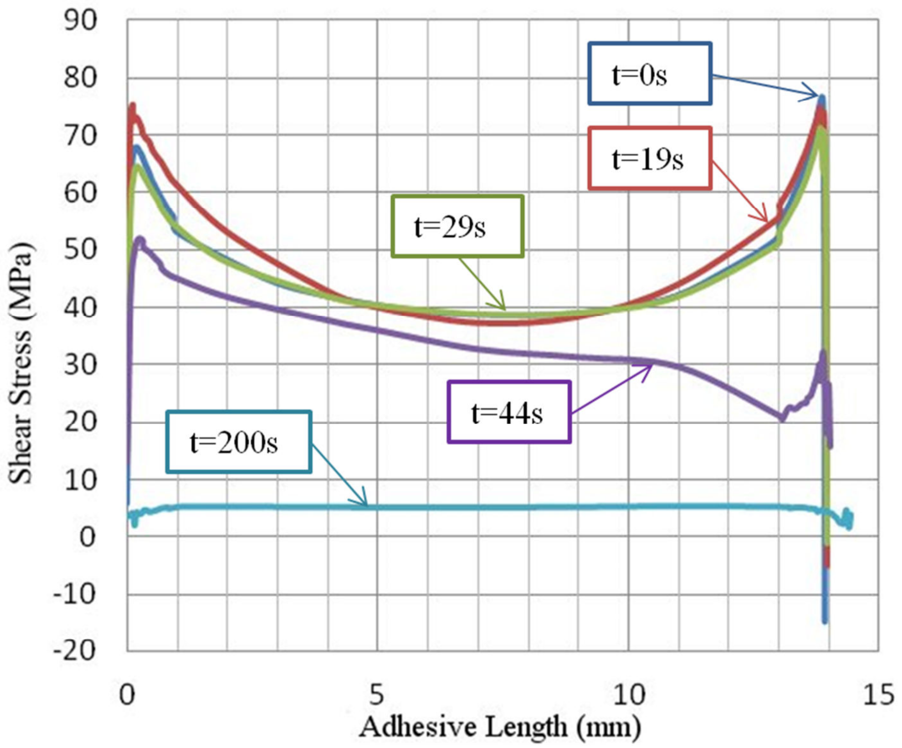

Fig. 13 - Stress distribution along the adhesive joint exposed to fire

It can be noticed that the stress intensifies at the borders as mentioned earlier. This was also observed in previous studies (Saleh, 2014). It is also obvious that the shear stress decreases dramatically after extended times of exposure to fire. This is surely due to the degradation of the mechanical properties of the epoxy adhesive as discussed in the previous section.
This work shows the variation of the stresses in the assembly subjected to fire and impact, as a function of the fire exposure time.

CONCLUSION

The first and most important conclusion of this study is that fire exposure, i.e. high temperatures, has a massive influence on composite structures and could quickly weaken them. As for our specific assembly, subject to fire and impact loading, it was observed that the most vulnerable zone is the adhesive showing major deterioration especially at the borders. The overall stress distribution through the adhesive layer also decreases enormously for extended periods of exposure as the rigidity of the material drops with elevated temperatures. This study would surely be an opening to several thermo-mechanical structural analysis of composites making it easier to predict the overall resistance of composite structures under fire.

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