A NEW SMALL SCALE FIRE RESISTANCE TEST METHOD FOR COMPOSITE MATERIALS

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SUMMARY

A new method has been developed for fire resistance testing of composite materials. Using this approach, composite panels have been subjected to combined fire and mechanical load in small scale tests. The results have shown a very similar trend in the degradation of panel stiffness regardless of small changes in panel thickness and volume fraction or ply orientation.

Keywords: Fire, testing, resistance, laminate, epoxy

INTRODUCTION

A major factor preventing further widespread use of polymeric single skin and sandwich materials is their behaviour in fire. The fire aboard the Norwegian composite mine hunter “Orkla” in 2002 [1] did much to harbour the belief that composite materials are not safe to be used in structures where there is a risk of fire. One of the root causes of the “Orkla” fire was an insufficient design standard. Whilst these regulations were not necessary for military craft it was stated in the accident report [1] that, had they been followed the severity of the incident would have been greatly reduced. The regulations cover many aspects of vessel design and operation; here the authors are concerned with the fire resistance of typical deck and bulkhead materials and the relevant testing that is required to be undertaken.

For vessels carrying more than 12 passengers or greater than 500 gross tons the International Maritime Organization (IMO) specify particular test standards which all materials onboard have to comply with [2]. In the fire resistance tests a section of a bulkhead or deck from a vessel 2.5m × 2.5m is subjected to a fire from one side. The temperature next to the panel is kept in line with the cellulosic temperature-time curve [2]. Static loads are also applied which match the loads that the structure would be subjected to in service. To pass the tests the panels must, over a specified time period, prevent the temperature on the cold surface rising above a threshold level in addition to supporting the load within a specified deflection. Due to the size of the specimens required, the tests are expensive, time consuming and are not necessarily an effective method for trialing different materials.

Experimental investigation of single skin polymer composites subjected to fire has been approached in a number of different ways. In terms of purely looking at the heat transfer through composites two approaches have been adopted. Firstly, testing panels from 0.3m × 0.3m up to around 3m × 3m in a furnace as carried out by Davies et al. [3] and Gibson et al. [4-8]. These test methods have used large scale furnaces to test panels. Secondly, work by Henderson et al. [9] showed what can be achieved with testing on a smaller scale. Here glass/phenolic samples were made in cylindrical form 100 mm in diameter by 30mm in length and insulated on all sides except the heat exposed face. This form of testing has produced results which have very closely matched predictions made by heat transfer modelling.

Combined fire and load testing has been carried out using apparatus which can subject 1m × 0.7m panels to in plane compressive and out of plane loads during fire by Dao and Asaro [10] and by subjecting tensile and compressive coupon samples to intense heat and fire during standard tests by Gibson et al. [6]. Both approaches have their advantages; the panel test method proposed by Dao and Asaro [10] can subject panels to compressive in plane loads or out of plane loads in the same manner as is required by the IMO regulations. The coupon tests can show the effects of thermal degradation on composites under individual forms of loading. This could then be used to predict the effects on larger structures. A drawback with this method is that the feedback to the fire from the volatiles released by the composite would have little effect compared to the heating, whereas on a larger scale these effects may affect the temperature to a greater extent.

The purpose of this paper is to describe a method of predicting the performance of composite materials in the full scale IMO tests using a small scale panel testing apparatus. The methods described above each have their own merits but currently there is lacking an approach to trial and compare different material solutions in preparation for the IMO testing.

APPARATUS DEVELOPMENT

Apparatus has been designed and built with certain criteria in mind, namely;

1. To perform a self contained assessment of a particular composite material’s performance in fire.
2. To assess thermal and mechanical effects of fire on a composite material.
3. To be portable and capable of using existing extraction systems in a laboratory.

Burner System

The fuel supply to the burner system is bottled propane. This was chosen over piped gas for reasons of portability. The burner system chosen is a Maxon® Kinemax MVG 70 30kW propane burner, which is attached to an 11kg propane bottle. The gas mixes with air in the cast refractory block where ignition takes place and a flame fires into the furnace. Before reaching the refractory block the gas passes through a series of valves and transducers checking the pressure is within set limits and preventing any suck back into the bottle. The air is drawn into the system through a motor driven rotating impeller which allows for the dusty atmosphere encountered in the laboratory. The stoichiometric ratio of gas to air is controlled mechanically by a steel rod linking the valves, allowing air and gas into the refractory block. This is set to allow excess air in to the mix to ensure complete combustion and minimise the risk of carbon monoxide being produced.

Furnace

To fit the furnace inside a fume cupboard and allow enough space for fire to circulate inside, high performance insulation was needed. The insulation could be up to 60mm thick and the temperature drop required was over 800^{o}C. The overall weight of the structure needed to be kept to a minimum in order that it could be supported inside a fume cupboard and this ruled out certain types of insulation material. A three layer approach was adopted to the insulation with the different materials each having their optimum insulating properties within different temperature bands. Starting from the inside of the furnace, the three layers are 25mm Keranap 50 Vacuum formed board 1260 grade, 5mm WDS ® Superflex Fibre panel and finally 30mm WDS ® ULTRA Fibre Board. The insulation is held in place on 5 sides of the furnace by a 1mm stainless steel box which sandwiches it in between the box and the outer furnace casing. This also served to protect the insulation from being eroded away by the fire. The burner system fits in to a circular opening on the side of the furnace and the flame fires through a 90^{o} tube into the furnace inline with the centre of the test panel. The front plate of the furnace is detachable and has a square opening which houses the test samples and onto which the loading module is fixed. An exhaust pipe, to vent the gaseous combustion products was fixed onto the side of the furnace as shown in Figure 1. In order to reduce the temperatures of the gasses from 1000^{o}C inside the furnace a water cooling system was employed. A pipe from a mains water supply is fixed to a nozzle near the exit of the exhaust, which sprays the water over the gasses. This reduces the temperature down to approximately 100^{o}C. The furnace is made from mild steel and measures 0.5m × 0.5m × 0.5m; one side is detachable, which houses the test samples. The samples are held in place with a square bracket as shown in Figure 2 by 8 M12 bolts. The samples are 0.24m × 0.24m with an area exposed to the heat source of 0.2m × 0.2m.

Loading System

A Powerjacks 50kN translating mechanical actuator was chosen and a 1.5kW BALDOR® DC motor was used to power the actuator, which was chosen over an AC motor for ease of control. The mechanical motor means that the system is portable and only requires mains electricity to operate. The whole module including the supporting structure weighs around 40kg and can be seen in Figure 3. The load is applied via a steel contact piece which is located in the centre of the panel and has a contact area of 40mm × 40mm. In order to achieve an even load over the area a rubber pad is attached to the end of the contact piece. This reduces the load being concentrated on the corners of the loading area. An insulating Teflon disc is fixed in between the actuator and the contact piece to reduce the heat conduction back to the load cell and displacement transducer.

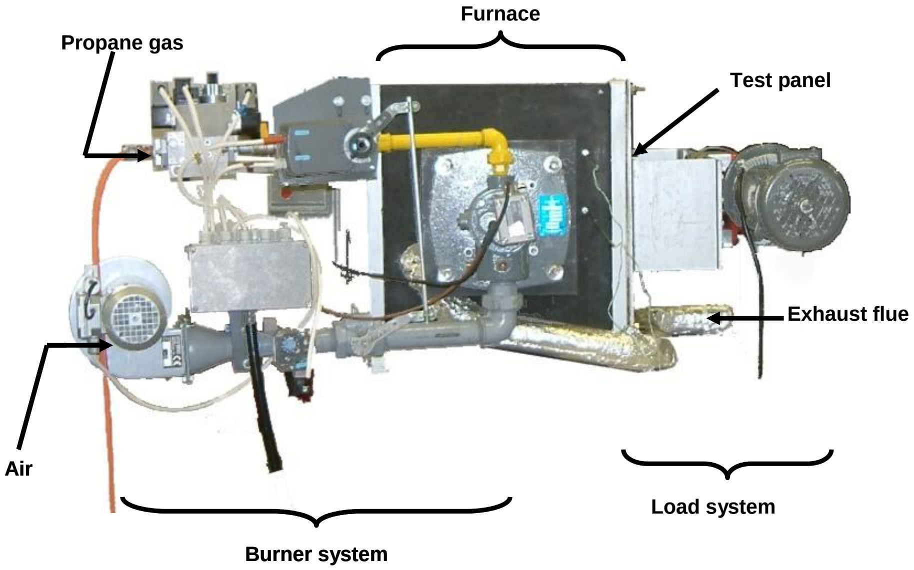


Figure 1: Full fire and load test system

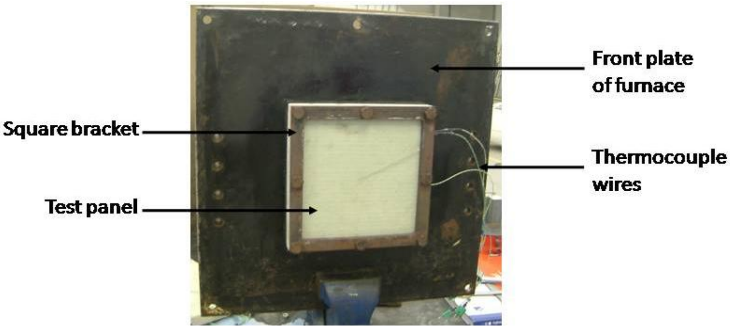


Figure 2: Panel attachment system as viewed from inside the furnace

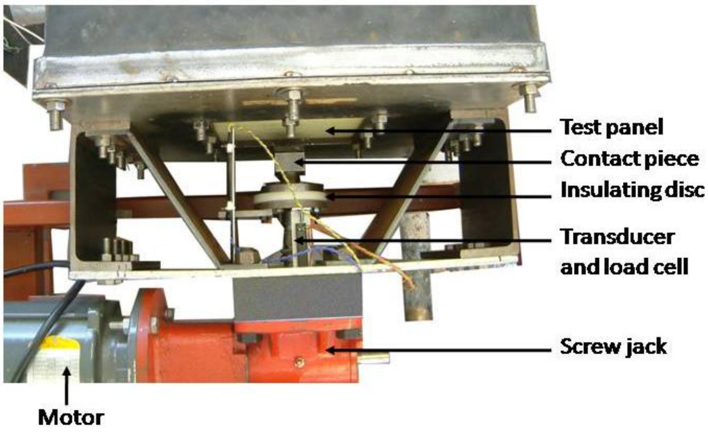


Figure 3: Loading module view from above

Control and Data Acquisition

The control for the burner is a self contained system which uses a thermocouple located inside the furnace as feedback. An Omron® E5CK-T Ramp/Soak Process Controller is used to control the opening of the gas valve to allow more or less gas into the furnace and change the temperature. This allows 16 set temperature points to be programmed into each pattern and has a sampling rate of 250 micro seconds. A fuzzy auto tuned PID control produces good transient response and a minimal overshoot upon adjustment of the gas flow. The system also has a series of safety cut offs which are triggered by the pressure switches in the gas train as well as an ultra violet flame detector which causes the system to shut down if there is no flame and so preventing a build-up of combustion gasses.

The load system is controlled through a Sprint Electric® 1600i control board via an analogue to digital converter from a PC using the DASYlab® software package. The board employs a closed loop control of both armature current and feedback voltage to give precise control of the motor torque and speed. The DASYlab® software is able to take inputs from a load cell, inline with the actuator, and displacement transducer, which measures the actuator displacement, and output a voltage that corresponds to a specific torque on the motor.

Temperatures inside the furnace and in the test panels are recorded using a variety of k-type thermocouples. Inside the furnace minerally insulated thermocouples have been employed while leaf type thermocouples have been used to measure the temperature on the unexposed surface of the test panels. Fibreglass insulated thermocouples were laminated inside the panels. On the exposed surface the method described by Urbas and Parker [12] in the surface temperature measurements of burning wood samples was used. Here two small diameter holes were drilled from the unexposed side of the sample 10mm apart through to the exposed face. The wires of a thermocouple were inserted through the holes so the hot junction was in contact with the exposed surface in between the holes. The thermocouple cable was then tightened so that the hot junction was kept in contact with the surface on the exposed side and any temperature gradient was eliminated which would conduct heat towards or away from the surface. With this method it was possible to be sure that the hot junction of the thermocouple was in good contact with the surface, even when the surface was receding. The thermocouples are plugged into a Picotech TC-08 thermocouple data logger which has 8 channels and allows the temperatures to be recorded directly onto a PC. More detailed specification of the burner and control system is given in Cutter [11].

A system diagram of the apparatus, named Vulcan, is shown in Figure 4.

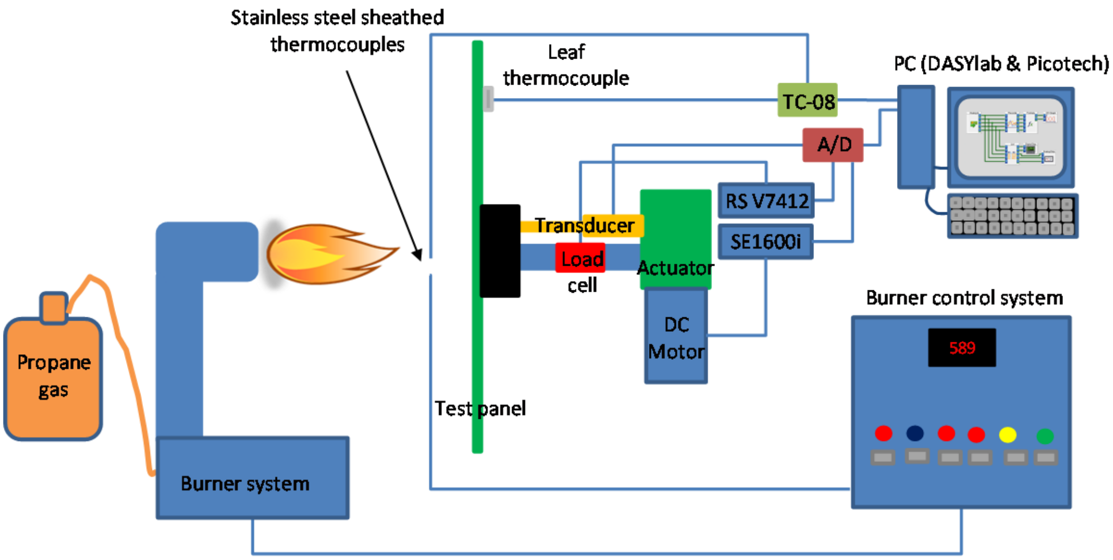


Figure 4: Vulcan- Fire resistance testing apparatus, system diagram

EXPERIMENTAL PROGRAMME

To assess the new test method a series of composite panels were tested under fire and also under fire and load in the Vulcan fire test apparatus. The ability of the furnace to follow a set temperature time curve was assessed and the recorded temperatures, load and deflection data were analysed.

In each case a panel was secured into the apparatus as shown in Figure 2. In the fire tests thermocouples were attached to the hot surface using the method described previously and to the cold surface using an epoxy adhesive.

In the combined fire and load tests the hot surface temperatures were not measured as it was thought drilling holes in the panels would affect the panels' strength and stiffness. For each test an out-of-plane load was applied to the panel and held at a constant value. When the set load had been reached, the furnace was started and the motor was held at a constant torque. The furnace temperature in each case was programmed to follow the cellulosic fire curve [2]. In each experiment the applied pressure, actuator displacement, furnace temperature and panel cold face temperatures were recorded at a rate of 1 Hz. The details of the tested panels are given in Table 1.

The different lay ups used are detailed in Table 1 using conventional ply lay up notation. All of the panels were made by wet lay-up technique and vacuum consolidation, which, in addition to extensive use of pre-pregs is one of the methods used in the construction of lifeboats. The resin used in each case was an epoxy laminating resin that has been optimised for open mould laminating of large structures. The reinforcements used were all stitched e-glass cloths/fibres of varying configurations.

Table 1: Test matrix for fire and load testing in Vulcan apparatus

Panel	**layup**	**Fibre volume fraction**	**Thickness (mm)**	**Pressure (MPa)**	**Duration (mm:ss)**
SS 1.1	$[0]_{16}$	0.41	10.7	4.4	08:10
SS 1.2	$[0]_{16}$	0.31	11.1	2.5	12:18
SS 2.1	$[0/90]_{8S}$	0.45	10.9	4.4	07:04
SS 3.1	$[\pm45]_{8S}$	0.33	12.2	4.4	07:41
SS 4.1	$[0]_{12}$	0.35	9.12	1.9	09:07
SS 5.1	$[0/90]_{6S}$	0.39	8.8	3.1	08:54
SS 6.1	$[\pm45]_{13}$	0.44	9.36	2.5	09:33
SS 6.2	$[\pm45]_{13}$	0.46	9.24	5.0	06:05

RESULTS

The furnace temperature was measured at a distance of 100mm from the hot surface of the test panels in each test and the average temperature reading showed a good similarity to the standard cellulosic curve [2] shown in Figure 5. The apparatus was able to follow the curve for up to 30 minutes before the temperature in the furnace was below the threshold level. The tests were all stopped inside this 30 minute period.

There was very little audible above the noise of the extraction system and the burner system throughout the tests. During the initial period of the tests there was a small amount of white smoke, emitted from the exhaust of the furnace, gradually becoming denser until about 50 seconds in to each test. By this point the smoke had become very dense and filled the fume cupboard. As the tests progressed smoke was escaping from the edge of the front plate of the furnace and from around the edges of the test panel.

Once each test was completed it was possible to examine the panels and the apparatus. A sticky and viscous black liquid was left on the inside of furnace around the area where the test panel was secured.

After each test, on the hot face of the panels, the resin had completely charred in every instance. The resin formed small clusters of a black char, which stuck to the fibres. The first few layers of fibres had become delaminated from the rest of the panel and were covered in the black char residue. Figure 6 shows the degradation, which occurred in the panels. For the longer duration test shown there was a small amount of decolouring of the cold side of the panel, which was not evident in the shorter duration test. It was also possible to see where the black liquid, previously mentioned, had flowed from the holes in the centre of the panel through which the thermocouple wires passed.

The heat transfer appeared to be mainly through the thickness. It can be seen in Figure 6 that the edges where the panel has been clamped have not charred. This indicates that the heat flow in the plane of the panels is minimal compared with the heat flow through their thickness.

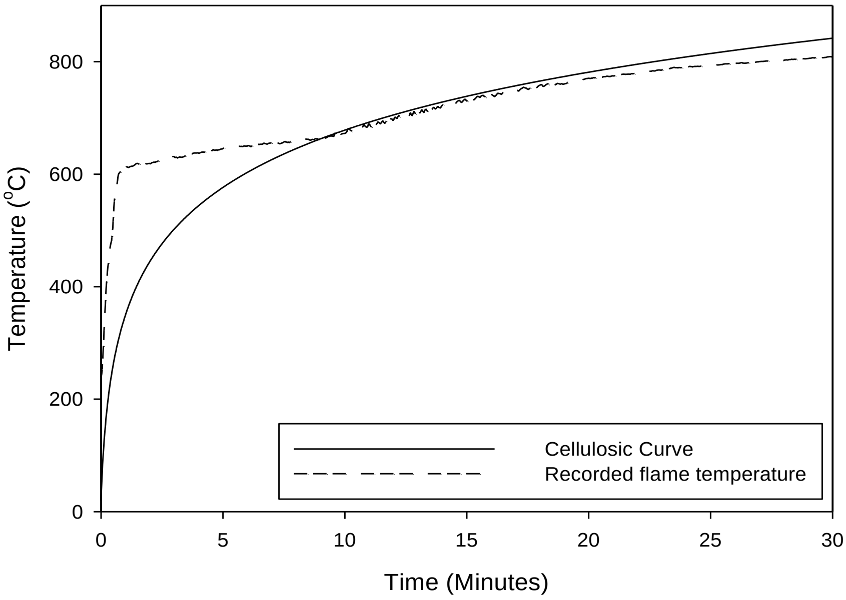
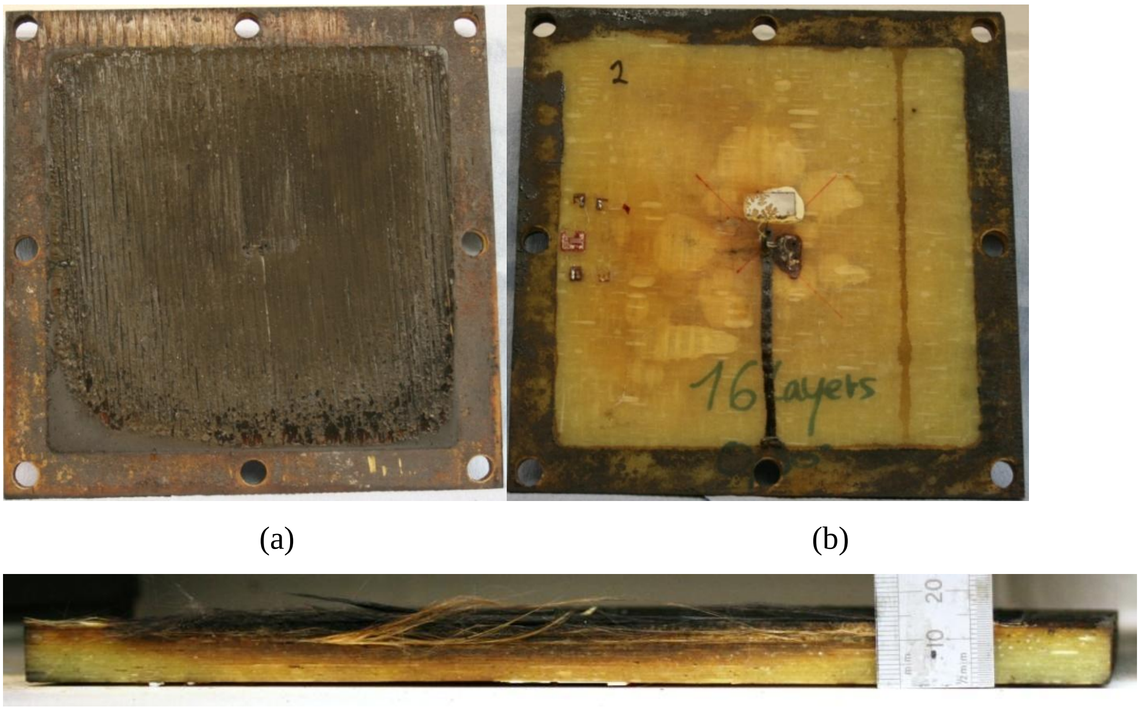


Figure 5: Flame temperatures from fire testing



(a) (b)

(c)

Figure 6: (a) Hot (b)cold and (c) cross section through panel centre after exposure to cellulosic fire for 20 minutes

In order to assess the relative performance of each of the panels, whilst being subjected to a cellulosic fire and load, the percentage change in stiffness has been calculated.

A finite element model was created using ANSYS® to model the loaded plate. This model was programmed to input the load and deflection, which were recorded during the experiments, and output an equivalent isotropic stiffness at thirty second intervals throughout the tests. The normalised decrease in stiffness was then calculated and is shown in Figure 7.

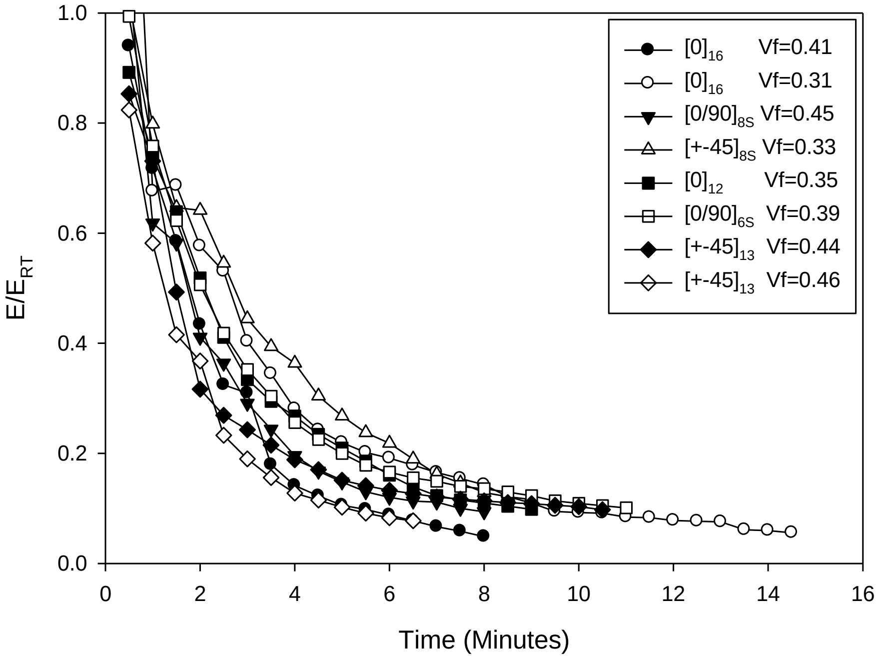


Figure 7: Normalised decrease in stiffness over time of composite panels subjected to combined load and cellulosic fire curve, E and E_{RT} represent the effective isotropic panel stiffness during the test and at room temperature

It is clearly shown in the figure that there is a definite trend in the results, which applies to all of the panels. There is a dramatic decrease quickly after the fire is started, with a 50% decrease on average after two minutes and a 75% decrease on average after four minutes. There is no clear difference in the performance of the different panels with different lay-ups, thickness or fibre volume fraction.

The stiffness of a panel subjected to fire at any given time will be a function of the temperature profile through the panel. The temperature profile through the panel under a given fire curve will be a function of the panel thickness, assuming all other panel properties remain constant. Therefore in order to scale the results from a thin panel tested in the Vulcan apparatus to a large scale panel a scale factor would need to be applied. However, the results shown in Figure 7 indicate that the percentage reduction in stiffness versus time is not sensitive to the panel thickness for the panels tested. The reason for this similarity may be due to the process by which the load is supported by the fibres in a tensile net. Initially as the load is applied the loaded (cold) face will be under compression and the unloaded (hot) face will be in tension. As the panel is heated and the resin degrades the load begins to be supported by the fibres alone. This will happen when the glass transition temperature is reached through the panel. As this occurs the loaded face will no longer be in compression but part of a tensile net. The net is held in place by the intact composite around the edges of the panel. Once this process has occurred it is proposed here that there is little variation in the stiffness of the fibres at elevated temperatures and this is why the results show similar levels of degradation between each panel type and regardless of lay up.

The results presented here show a good agreement with previous published work. Gibson et al. [6] conducted flexural tests on single skin coupon samples while subjecting them to a heat flux of 50kW/m^2. For glass reinforced polyester laminates the results indicate that by 2 minutes the stiffness had decreased by 50%. For a glass reinforced phenolic laminate the results show the stiffness to have decreased by approximately 20%. The results from previous authors' work on similar materials agree well with the results presented here. The form of loading differs in each case but the rate at which the stiffness of single skin and sandwich materials decrease in a given fire seem to correlate.

In previous works the emphasis has been on conducting coupon tests under tensile or compressive loading whilst being subjected to a constant heat flux [6, 15]. These investigations have concentrated on determining the strength of the given materials. The experimental results and methods given here concentrate on the stiffness of the panels under constant load and a standard temperature time curve. This will prove very useful to designers needing to predict the effect of fire and mechanical load during service and during a regulatory fire resistance test.

CONCLUSION

A new test method has been developed here that is capable of subjecting single skin panels to combined fire and load. The apparatus that has been developed has been shown to be capable of subjecting small composite test panels to conditions representative of the full scale fire tests. The measured temperatures inside the furnace followed the standard BS 476 cellulosic fire curve for the first 30 minutes within the allowable limits. This will allow future users to compare the insulating performance of different materials in a fire at small scale in a fast and economical manner. It will also give an indication to the fire rating of different materials for use in ship structures.

A series of tests were also carried out under fire and load and the results showed that all the panels tested undergo a rapid loss of stiffness whilst being subjected to a cellulosic fire. A decrease in stiffness of 50% occurs within the first two minutes and 75% within four minutes.

ACKNOWLEDGEMENTS

This work has been entirely funded by the Royal National Lifeboat Institution (RNLI) via their Advanced Technology Partnership (ATP) with the University of Southampton.

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