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Numerical Simulation of Thermal Performance of Glass-Fibre-Reinforced Polymer

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Abstract. Glass-Fibre-Reinforced Polymer (GFRP), as a developing construction material, has a rapidly increasing application in civil engineering especially bridge engineering area these years, mainly used as decorating materials and reinforcing bars for now. Compared with traditional construction material, these kinds of composite material have obvious advantages such as high strength, low density, resistance to corrosion and ease of processing. There are different processing methods to form members, such as pultrusion and resin transfer moulding (RTM) methods, which process into desired shape directly through raw material; meanwhile, GFRP, as a polymer composite, possesses several particular physical and mechanical properties, and the thermal property is one of them. The matrix material, polymer, performs special after heated and endue these composite material a potential hot processing property, but also a poor fire resistance. This paper focuses on thermal performance of GFRP as panels and corresponding researches are conducted. First, dynamic thermomechanical analysis (DMA) experiment is conducted to obtain the glass transition temperature (Tg) of the object GFRP, and the curve of bending elastic modulus with temperature is calculated according to the experimental data. Then compute and estimate the values of other various thermal parameters through DMA experiment and other literatures, and conduct numerical simulation under two condition respectively: (1) the heat transfer process of GFRP panel in which the panel would be heated directly on the surface above Tg, and the hot processing under this temperature field; (2) physical and mechanical performance of GFRP panel under fire condition. Condition (1) is mainly used to guide the development of high temperature processing equipment, and condition (2) indicates that GFRP's performance under fire is unsatisfactory, measures must be taken when being adopted. Since composite materials' properties differ from each other and their high temperature parameters can't be obtained through common methods, some parameters are estimated, the simulation is to guide the actual high temperature experiment, and the parameters will also be adjusted by then.

1. Introduction

Fibre reinforced polymer, which possesses excellent mechanical properties, was developed as an aerospace material initially, and has been introduced into civil industry area these years. As a representative of composite material, glass fibre reinforced polymer (GFRP) is adopted widely because of its mature craftwork and relatively cheap price. In civil engineering field, GFRP was first adopted as a spire of a church in British Smethwick, 1961 [1] and for now is mainly used as decorating and bar material in structural area and decks in the bridge area [2]. Most composite materials have advantages in respects of self-weight, strength, resistance to corrosion and ease of processing over

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traditional building materials. In addition to form members directly through raw materials, GFRP's thermal properties could also be utilized to process panels into curved shape, but also make this material's fire performance worrying, thus its fire resistance property has always been a research emphasis. GFRP's physical and mechanical properties would change obviously when heated, and sudden change might occur at several temperatures, which is also a characteristic of composite material as mixture.

This paper mainly focuses on thermal properties of GFRP and corresponding research is carried out. First, Tg (glass transition temperature) is obtained through DMA (Dynamic Thermomechanical Analysis), and the relationship curve between bending elastic modulus and temperature is calculated through data. Then according to relevant literature, obtain and compute other thermal parameters and conduct numerical simulation of GFRP under two conditions: (1) simulate heat transmission process in which heat GFRP panel directly up to Tg and then conduct hot processing under the temperature field; (2) simulate GFRP's performance in fire.

2. GFRP material properties and DMA

2.1. Object GFRP

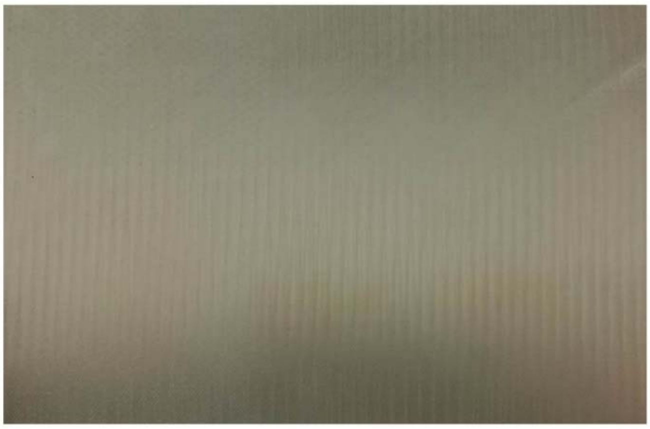

Figure 1. Object GFRP

The object GFRP is shown as figure 1, which takes epoxy resin as matrix and E-glass glass fibre as reinforcing material. The glass fibre mass fraction is 70% and arrange in ±45°direction. The mechanical properties of materials at 20°C are shown in table 1.

Table 1. Mechanical properties of GFRP at 20°C

Density kg/m3	Longitudinal bending modulus of elasticity MPa	Longitudinal bending strength MPa	Transverse modulus of elasticity MPa
2000	16000	140	3000

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GFRP, as a composite material, is a typical anisotropic materials, of which longitudinal (strengthen direction) strength and modulus of every layer is obviously higher than transverse direction (vertical to strengthen direction), and its strength and modulus of transverse direction is based on matrix material, but higher than pure epoxy resin. It is also worth mentioning that bending modulus of elasticity should be adopted in this research but tensile modulus, as the panel is mainly bear bending load that makes it more accurate. The state of polymer differs when temperature changes, but it is different from common material. At room temperature, the state of epoxy resin, the matrix of GFRP, is glassy state with a relatively high elastic modulus; when the temperature is higher than Tg, epoxy resin will enter elastomeric state, in which polymer would perform like rubber: with a pretty low elastic modulus but high plasticity and this is the potential hot processing property. So as for GFRP, there are two temperature which would change the state, Tg and softening temperature of glass fibre. Besides elastic modulus which will be obtained through DMA, other properties are considered as follows: a. specific heat: average 1000 J/(kg·K) from 0 to 200 °C, and 1500 J/(kg·K) from 0 to 1200°C b. thermal conductivity: 1 W/(m·K) in longitudinal direction, 0.5 W/(m·K) in transverse and depth direction; c. linear expansivity is shown as table 2, the value between the temperature can be taken as linear interpolation.

Table 2. Linear expansivity of GFRP

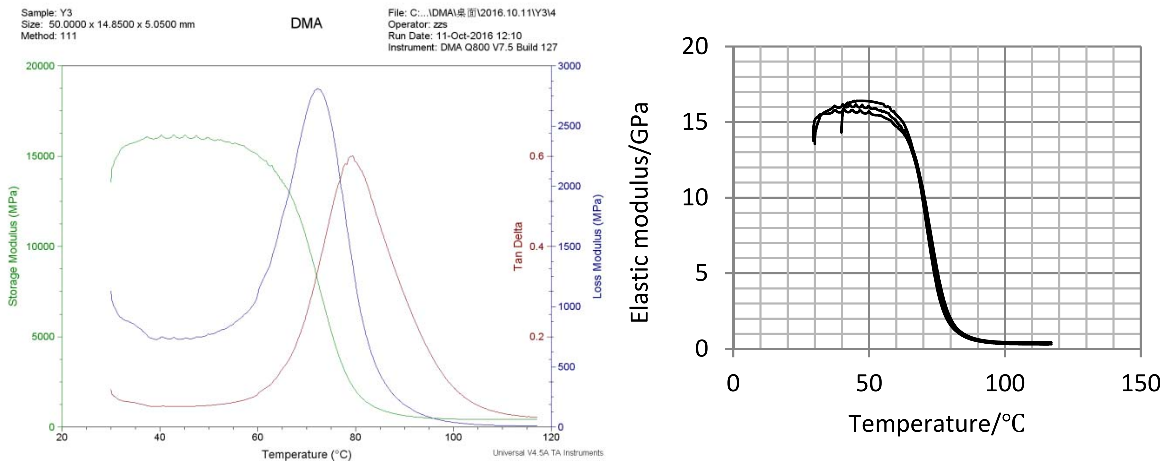
Temperature K	Longitudinal K^{-1}	Transverse K^{-1}	Depth K^{-1}
0	4.00E-06	3.50E-05	3.50E-05
353	4.00E-06	3.50E-05	3.50E-05
393	4.00E-06	7.50E-05	7.50E-05
773	4.00E-06	7.50E-05	7.50E-05
873	3.50E-05	7.50E-05	7.50E-05
1673	3.50E-05	7.50E-05	7.50E-05

The properties above may be slightly different from the actual material, such as the specific heat of 200°C is obtaining through Differential Scanning Calorimetry and is accurate, but it is difficult to measure directly when temperature is 1200°C, so the value is estimate by sharp method [3] and need to be adjusted by actual test.

2.2. DMA

DMA is to measure the relationship between viscoelastic material's properties and time, temperature or frequency, thus DMA can be used to measure a variety of material properties parameters. Here is the brief principle of DMA: polymer is a kind of viscoelastic material, which can store mechanical energy like elastic material, but can also consume energy like viscous liquid at the same time. When polymer deforms, some of the energy is stored into potential energy while the rest are consumed and turn into heat. When temperature changes, the storage modulus, loss modulus and loss tangent would change, and sudden change would occur around Tg. Therefore, Tg and the curve of GFRP elastic modulus with temperature can be obtained through DMA.

Figure 2. DMA equipment：DMA Q800



a) Result of one specimen b) Elastic modulus

Figure 3. DMA test result

Figure 3.(a) is a DMA test result of one typical specimen, there exist a peak between 70°C to 80 °C on loss modulus and loss tangent respectively, which indicates Tg of the specimen is around 70°C to 80 °C, and other specimens are similar. Figure 3. (b) is the curve of elastic modulus of three specimen between 30°C to 120°C, calculated from DMA data. The modulus decreases rapidly when temperature is around Tg and after 100°C, it is about two orders of magnitude lower than 30°C, but won't decrease anymore and actually the plasticity increases a lot now. So it can be concluded that the ideal processing temperature is over 100°C, and hot processing temperature is determined at 120°C. In the following condition (1), the panel will be heated over 393K first and process

3. Condition (1): numerical simulation of GFRP hot processing

This simulation is to guide the development of processing equipment and actual experiment, so that some mistakes can be prevented then. There are two steps of this simulation, first step is heating and thermal transmission of GFRP, and then deform the heated panel by loading.

ABAQUS finite element analysis software is used to conduct numerical simulation. Build GFRP panel model as shown in figure 5, the dimension is 1m x 1m x 4.8mm, 8 layers in total and 0.6mm each layer; the reinforcing direction is ±45°in order and material properties is imported as section 2.

First, simulate the thermal transmission process calculate heating time and heated temperature field of the panel. Mash the panel, adopt heat transfer element type DS8, set absolute zero to 0 and Stefan-Boltzmann constant to 5.67E-8. The boundary condition is 473K on one surface to simulate one side heating at 200°C, and both the surrounding temperature and initial temperature of material are 293K . The film coefficient of the heating surface is 0 W/(m^2·K) and 8 W/(m^2·K), which is the value of natural heat transfer coefficient, on the other surface, and take emissivity of GFRP as 0.9. Conduct transient heat transfer analysis and the result, temperature of unheated surface, is shown in figure 5. At the time of 50.3s, the temperature of unheated surface is 398.8K, and this is the moment when the whole section of the panel is over 393K and reach processing condition.

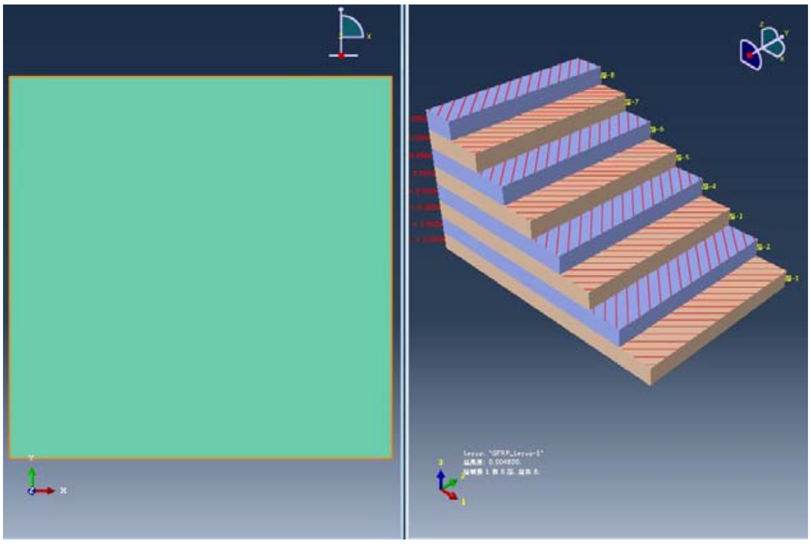


Figure 4. GFRP model

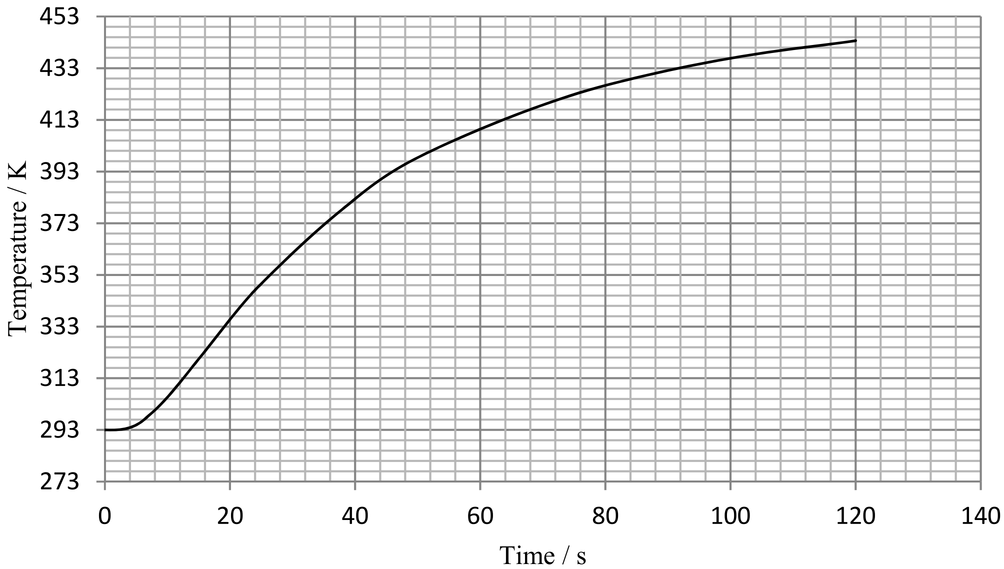


Figure 5. Temperature curve of unheated surface

Next step is to deform the panel on this temperature field, which needs to conduct a coupled temp-displacement analysis. So build the model again, mesh the panel and adopt coupled temperature-displacement element type S4RT, simply supported on four sides, import the temperature field of last step, arrange 9 concentrated loads (figure 6) in the centre to simulate extrusion load of actual processing. The target state is to cause 200mm vertical displacement in the centre point since this deformation can exceed largest deformation of panels made of other materials. When the force of every concentrated load is 1300N, the vertical displacement in the centre is 198mm, figure 7 shows the deformed shape of the panel and Mises stress of single layers.

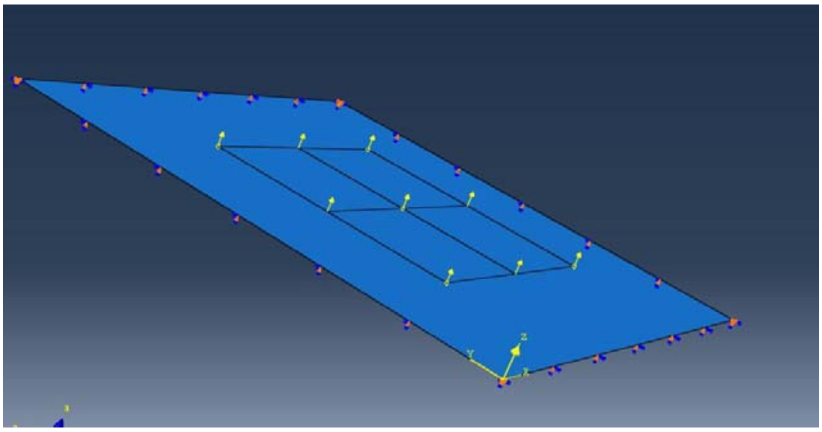
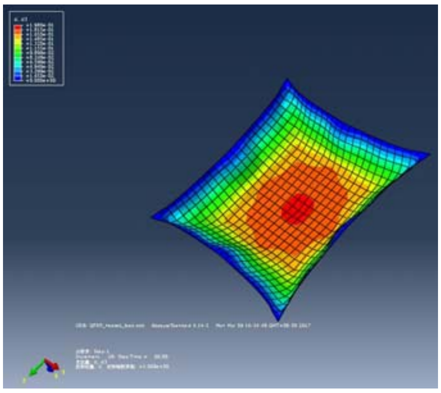
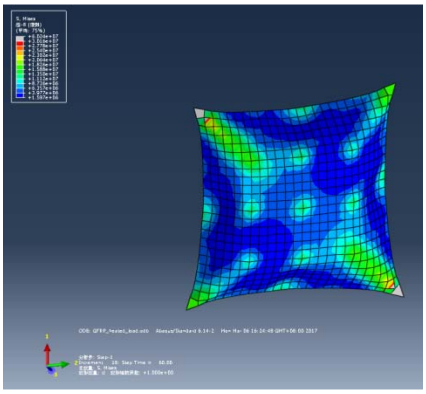


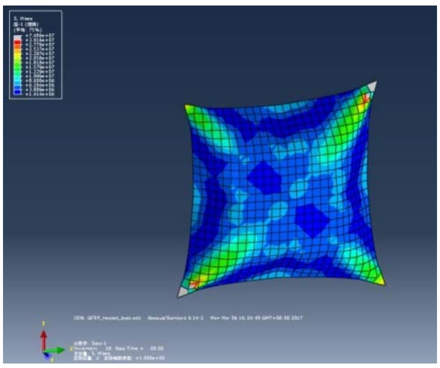
Figure 6. Load position on the panel



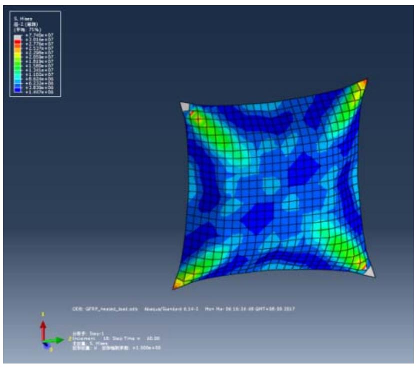
a) Deformation



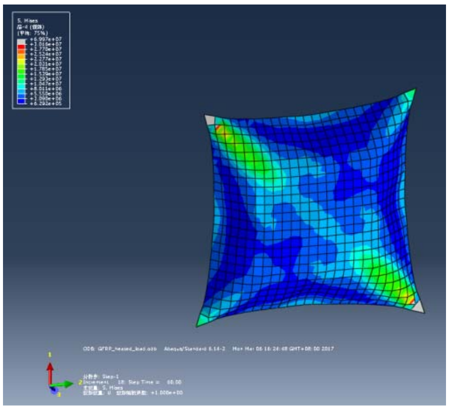
b) Mises stress of layer-8 on the top



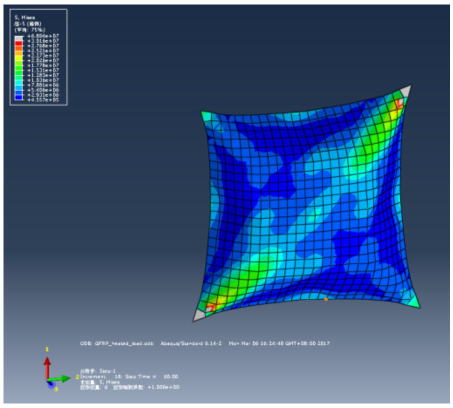
c) Mises stress layer-1 on the top



d) Mises stress layer-2 at the bottom



e) Mises stress layer-4 on the top



f) Mises stress layer-5at the bottom

Figure 7. Mises stress of layers

4. Condition (2): numerical simulation of GFRP under fire condition

Fire condition is much different from processing, the heat transfer depend most on thermal convection and radiation and the surrounding temperature keeps rising, thus the situation is relatively complicated. The model is same as condition (1), but import properties at 1200°C. Set film coefficient of expose-to-fire surface as 25 W/(m^2·K) according to Eurocode, [4] and 8 W/(m^2·K) on the back surface, then set surrounding fire temperature according to ISO-834, [5] and 293K on the back. The results, temperature curves of both sides, are shown in figure 8. Meanwhile, attempts are made to improve the fire performance by painting coating and using sandwich panel. The temperature of the panel which painted 1mm coating on the surface are shown in figure 9 (a) and sandwich panel with 10mm core material in figure 9 (b).

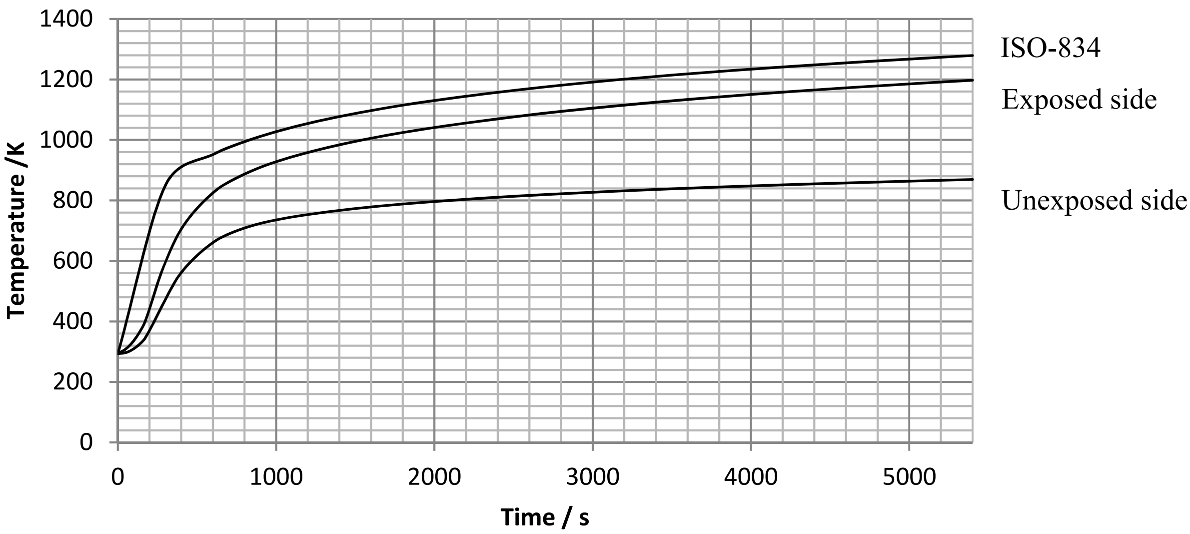
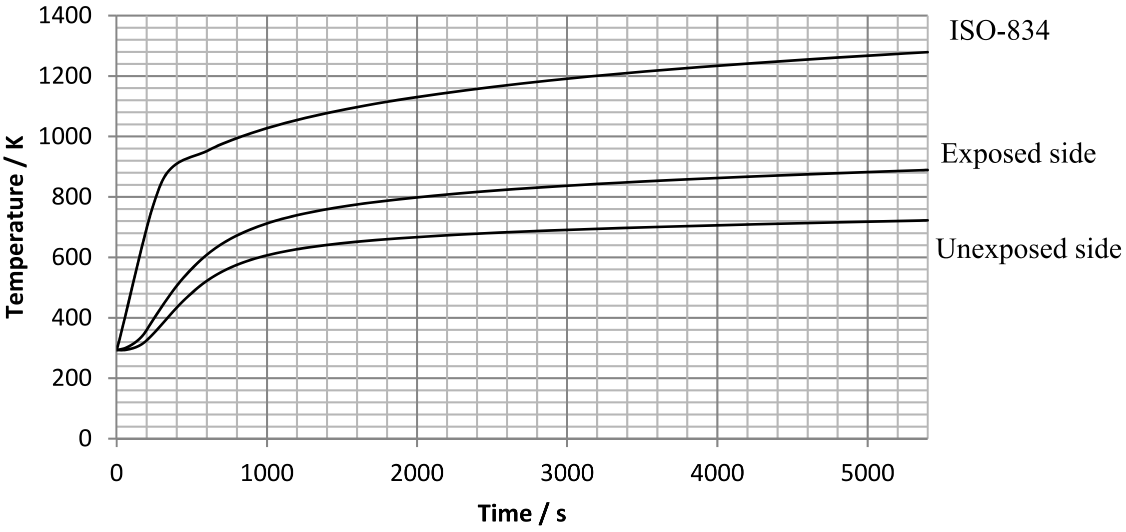
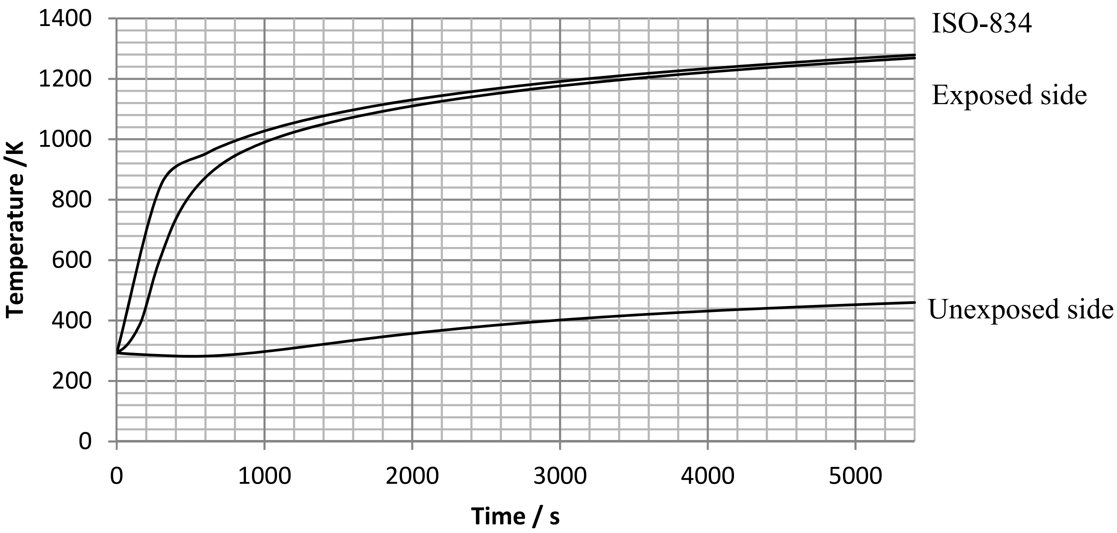


Figure 8. Temperature of GFRP panel exposed to fire



a) 1 mm coating on the surface



b) Sandwich panel

Figure 9. Temperature of treated GFRP

5. Results and discussions

5.1. GFRP hot processing

The original 16GPa elastic modulus is only 0.3GPa after heated, and only with 9 concentrated load, 11.7kN in total, can cause 198mm deformation in the centre with a max Mises stress of 30MPa, thus easy to process. There is hysteresis between load and deformation for polymer over Tg, the molecules flow gradually after loaded and cause plastic deformation, which takes a period of time. Therefore, the load might descend to keep the deformation after a while and plastic deformation would maintain.

The stress nephograms in figure 7 indicate obvious anisotropy property of composite material. Such as (e) and (f) of figure 7, which represent the stress nephogram of layer-4 on the top and layer-5 on the bottom respectively, two surfaces are at the same position, which is in the middle of the panel,

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and stick to each other but belong to different layer. The stress nephogram of two layer is symmetrical since the reinforcing direction bears the load mainly. This interlaminar shear is a main failure reason of composite material.

5.2. GFRP under fire condition

Figure 8 shows that GFRP's performance is unsatisfied under fire temperature. The temperature on the exposed side rises rapidly. Untreated epoxy resin, the matrix, is a kind of polymer and might carbonized or even start to burn at 600°C; and according to GB/T 9978-1 [6], the material loses heat insulation property when the temperature of unexposed side rise 140°C, which means 5 minutes for GFRP, and that is far less than the minimum requirements of 30 minutes. According to the curve in figure 9 (a), the coating can slow down the temperature rising speed of GFRP, and in addition, coating can help to isolate oxygen (air) from the panel and keep it stable; the curve in figure 9 (b) shows that sandwich panel possess better heat insulation property, the temperature of its unexposed side reach 410K at the time of about 4000s.

6. Conclusions

The thermal performance is studied in this paper through test and numerical simulation, the conclusions are as follows:

a. Obtain GFRP's Tg and curve of elastic modulus with temperature through DMA. When temperature is over 100°C, GFRP's elastic modulus would descend 2 order of magnitude and become processible;
b. Simulate GFRP's hot processing situation. It takes about 50s to heat the whole panel up to 120°C when the heating temperature is 200°C from one side, and 9 concentrated loads, 11.7kN in total, can cause 198mm deformation in the centre of the panel under this temperature field , which can satisfy most demands in civil engineering area;
c. GFRP panel must be treated considered fire situation, and surface coating and sandwich panel can improve its fire performance.

This paper can be a guidance for actual experiment, while there may be a certain amount of errors since some factors are estimated, also the specific conclusions and parameters need to be adjusted by further practical experiment.

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