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Fatigue behavior of basalt-aramid and basalt-carbon hybrid fiber reinforced polymer sheets

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Abstract: In order to study the fatigue failure mode and fatigue life laws of basalt-aramid and basalt-carbon hybrid fiber reinforced polymer (FRP) sheets, fatigue experiments are carried out, considering two hybrid ratios of 1∶1 and 2∶1 under different stress levels from 0.6 to 0.95. The results show that fractures occur first in carbon fibers or aramid fibers for the specimens with hybrid ratio of 1∶1, namely B1A1 and B1C1, while a fracture occurs first in basalt fibers for the specimens with a hybrid ratio of 2∶1, namely B2A1 and B2C1. The fatigue lives of the hybrid FRP sheets increase with the improvement of the content of carbon fibers or aramid fibers, and the influence of the carbon fibers content improvement to fatigue life is more significant. The fatigue performance of B2A1 is relatively worse, while the fatigue performance of B1C1 and B2C1 is relatively better. Finally, a new fatigue stiffness degradation model with dual variables and double inflection points is presented, which is applicable to both hybrid and normal FRP sheets.

Key words: hybrid fiber reinforced polymer sheet; basalt-aramid; basalt-carbon; fatigue experiment; stiffness degradation model

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Currently, some fatigue life models for normal fiber reinforced polymer (FRP) sheets have been presented by Reifsnider et al[1-3]. Wu[4] presented a fatigue life model for multilayer hybrid FRP sheets. Some researchers[5-14] also presented fatigue stiffness degradation models for normal FRP sheets. However, there are very few studies on the fatigue behavior of intraply hybrid sheets, especially for the basalt-aramid and basalt-carbon hybrid FRP sheets. In order to research the fatigue behavior of basalt-aramid and basalt-carbon hybrid FRP sheets, fatigue experiments with two hybrid types (basalt-aramid, referred to as B-A; basalt-carbon, referred to as B-C) and two hybrid ratios (1∶1 and 2∶1) under different stress levels (from 0.6 to 0.95) are carried out. The hybrid FRP sheets are made by the wet-layup method [15] according to GB/T 3354—1999[16] and GB/T 1447—2005[17]. The details of size and preparation of the specimens are the same as Ref. [15]. The stress ratios are all 0.1. The experiments are carried out in the Laboratory of Structural Strength in Nanjing University of Aeronautics and Astronautics. The main instrument is an electro-hydraulic servo fatigue experimental machine.

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1 Fatigue Experiments

Some typical damage occurred in the specimens during experiments, such as partial fibers failure, edge fractures, central holes, etc., as shown in Fig. 1.

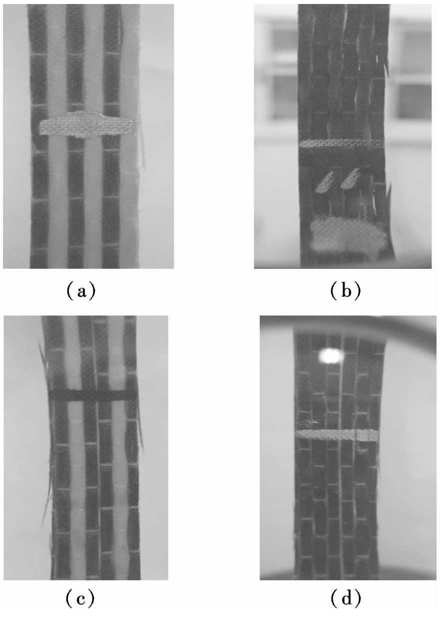

Fig. 1 Damage of the specimens during experiments. (a) B1A1; (b) B1C1; (c) B2A1; (d) B2C1

The final failure modes are all sudden brittle fractures, and all the specimens are incomplete after failure. Fractures occur first in carbon fibers or aramid fibers for the specimens with a hybrid ratio of 1∶1 (namely B1A1 and B1C1) (see Fig. 2), while fractures occur first in basalt fibers for the specimens with a hybrid ratio of 2∶1 (namely B2A1 and B2C1) (see Fig. 3).

The fatigue lives under different stress levels are shown in Fig. 4.

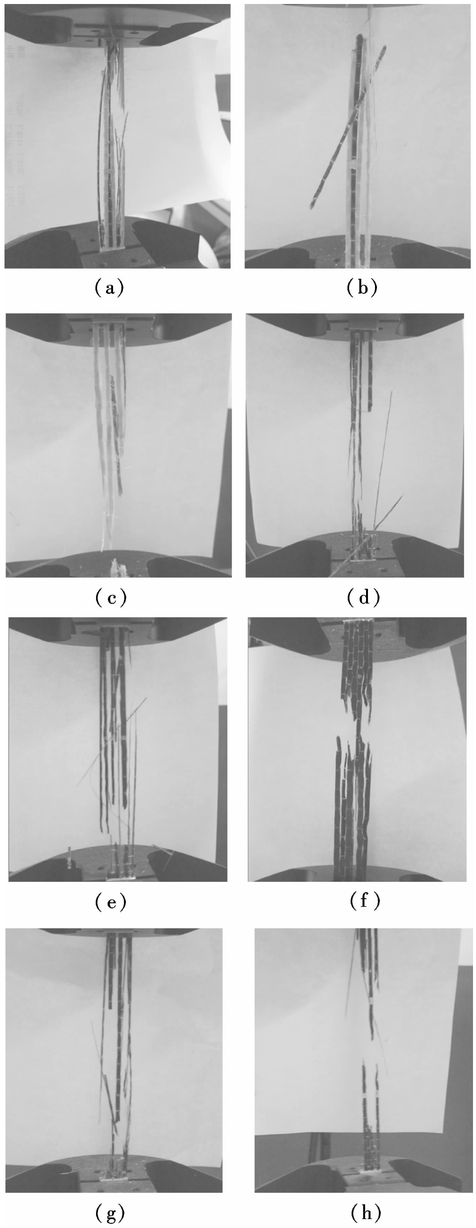

Fig. 2 Failure modes of the specimens with hybrid ratio of 1∶1. (a) B1A1-1; (b) B1A1-2; (c) B1A1-3; (d) B1C1-1; (e) B1C1-2; (f) B1C1-3; (g) B1C1-4; (h) B1C1-5

1) The fatigue lives of B-C sheets are higher than those of B-A sheets under the same stress level.

2) The fatigue lives of the hybrid FRP sheets increase with the improvement of the content of carbon fiber or aramid fiber, and the influence of the carbon fiber content improvement to fatigue life is more significant.

3) The fatigue performance of B2A1 is relatively worse, while the fatigue performance of B1C1 and B2C1 is relatively better. B1A1 is at the middle position.

4) When hybrid FRP sheets are used in the strengthening of engineering structures, in order to ensure the fatigue strengthening effect, it is recommended to adopt B1C1, B2C1, B1A1, and the stress levels should be below 70%.

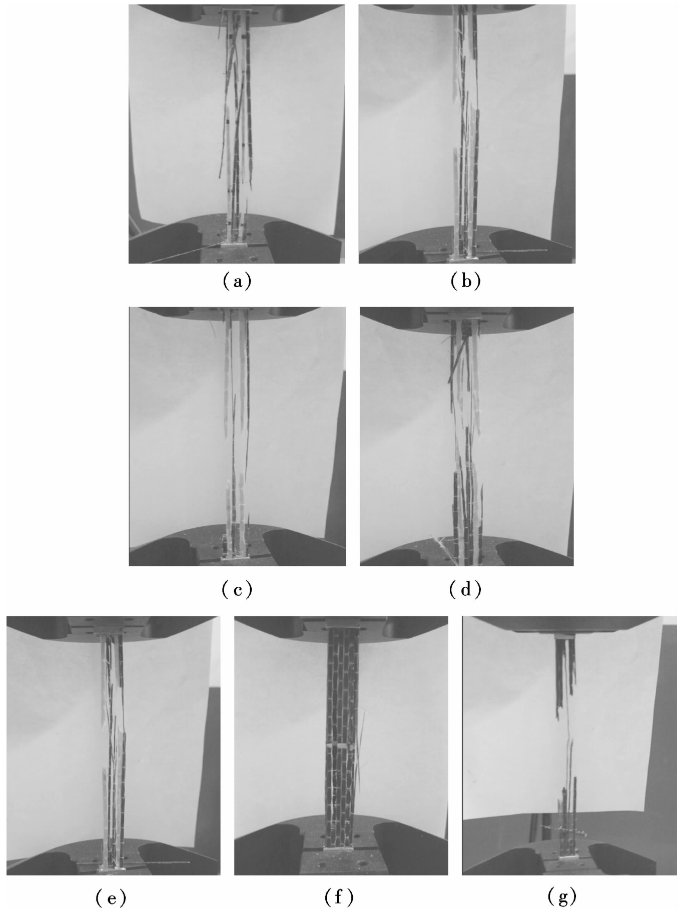

Fig. 3 Failure modes of the specimens with hybrid ratio of 2∶1. (a) B2A1-1; (b) B2A1-2; (c) B2A1-3; (d) B2A1-4; (e) B2A1-5; (f) B2C1-1; (g) B2C1-3

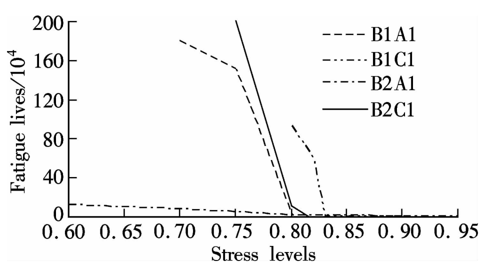

Fig. 4 Fatigue lives under different stress levels

2 Fatigue Life Models

Four existing fatigue life models presented by other researchers are used to fit the experimental data, including the models from Refs. [1 − 4], and the results are shown in Tab. 1. Results show that the fitting accuracy and generalization capability of the model in Ref. [2] is relatively

Tab. 1 Square of correlation coefficient of different models on experimental data

Specimen	Ref. [1]	Ref. [2]	Ref. [3]	Ref. [4]
B2A1	0.907	0.970	0.968	0.929
B2C1	0.727	0.763	0.661	0.734
B1A1	0.778	0.784	0.779	0.779
B1C1	0.654	0.633	0.692	0.650

better on experimental data of four types of intraply hybrid FRP sheets.

3 Stiffness Degradation Models

Eight existing fatigue stiffness degradation models presented by other researchers are used to fit the experimental data, including the models of Refs. [5 – 14]. The results show that, considering the fitting accuracy and generalization ability, the model of Ref. [14] is the relatively best model. However, the experimental data curve show two inflection points. The first inflection point is caused by damage in the matrix material due to the initial loading, and the second inflection point usually appears near the final failure. But all the existing models have only one inflection point, and thus need to be improved.

Based on the experimental data, a new fatigue stiffness degradation model with dual variables and double inflection points is presented as follows:

$$E(n) = E(0)\left(1 - \frac{n}{N}\right)^{r} + C(\ln n)^{2}$$

where n is the cycle number; N is the fatigue life; E is the stiffness; $E(0)$ is the original stiffness; $E(n)$ is the residual stiffness after n cycles; r and C are the experimental constants. According to the experimental data of this paper, it is recommended that $r = 0.01$ and $C = -22.3$.

This new model can be used to predict the fatigue stiffness degradation of basalt-aramid and basalt-carbon hybrid FRP sheets. Two sets of experimental data referred to as data(1) and data(2), respectively, from Ref. [14] are also used to verify this new model to see if it is applicable to normal FRP sheets, and the results are shown in Fig. 5.

From Figs. 5(a) and (b), we can see that the experimental data curve has two inflection points and the fitting curve of the new model also has two inflection points, while the fitting curve of the model of Ref. [14] only has one inflection point, so the new model has relatively better curve fitting result when the experimental data curve has two inflection points. From Figs. 5(c) and (d), we can see that the new model has also a relatively better curve fitting result when the experimental data curve has only one inflection point. Therefore, the new model is also applicable to predict the fatigue stiffness degradation of normal FRP sheets.

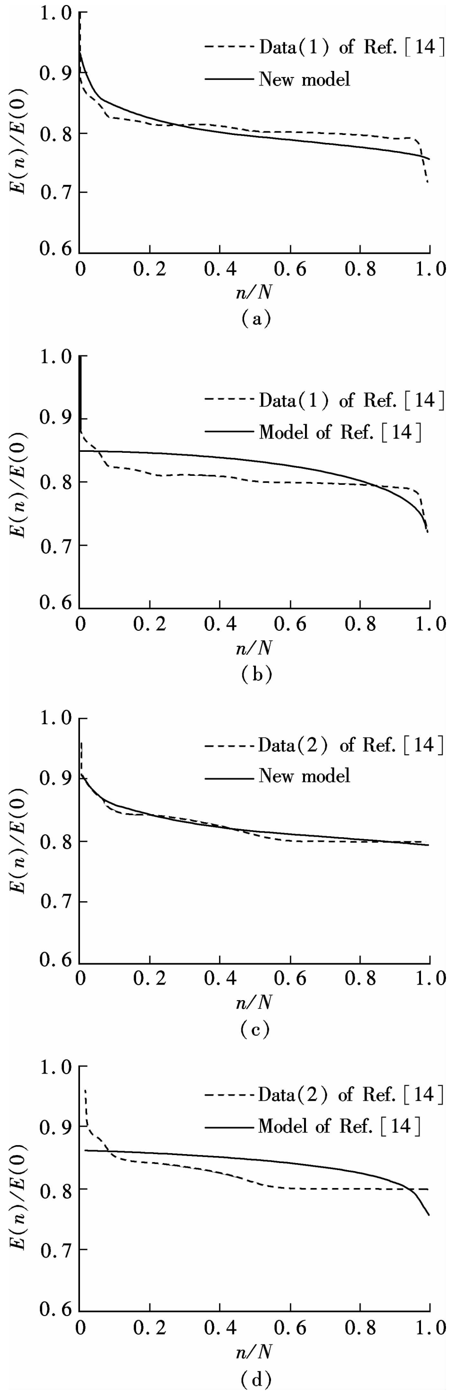

Fig. 5 New model vs. model of Ref. [14]. (a) The new model fitting the data(1) of Ref. [14]; (b) The model of Ref. [14] fitting the data(1) of Ref. [14]; (c) New model fitting the data(2) of Ref. [14]; (d) The model of Ref. [14] fitting the data(2) of Ref. [14]

4 Conclusions

Fatigue experiments on hybrid fiber reinforced polymer sheets with two hybrid types and two hybrid ratios (1∶1 and 2∶1) under different stress levels (from 0.6 to 0.95) are carried out. Conclusions are as follows:

1) The fatigue lives of B-C hybrid FRP sheets are higher than those of B-A hybrid FRP sheets. The fatigue lives of the hybrid FRP sheets increase with the improvement of the content of carbon fibers or aramid fibers, and the influence of the carbon fibers content improvement to fatigue life is more significant.

2) The fatigue performance of B2A1 is relatively worse, while the fatigue performance of B1C1 and B2C1 is relatively better. B1A1 is at the middle position. When hybrid FRP sheets are used in the strengthening of engineering structures, in order to ensure the fatigue strengthening effect, it is recommended to adopt B1C1, B2C1,

and the stress levels should be below 70%.

3) In the four existing fatigue life prediction models, according to the fitting accuracy to the experimental data of hybrid FRP sheets, the model of Ref. [2] is the relatively best one. In the eight existing fatigue stiffness degradation models, according to the fitting accuracy and generalization capability to the experimental data of hybrid FRP sheets, the model of Ref. [14] is relatively the best one. However, the experimental data curves often show two inflection points, but all the existing models have only one inflection point, and thus need to be improved.

4) A new fatigue stiffness degradation model with dual variables and double inflection points is presented, which is not only applicable to hybrid FRP sheets, but also applicable to normal FRP sheets, so it has a wider range of application.

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玄武岩-芳纶和玄武岩-碳混杂纤维增强复合材料片材的疲劳性能

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摘要:为了研究玄武岩-芳纶和玄武岩-碳混杂纤维增强复合材料(FRP)片材的疲劳破坏形态和疲劳寿命规律,进行了2种混杂比(1∶1和2∶1)的片材试件在0.6~0.95应力水平下的疲劳试验.试验结果表明,对于混杂比为1∶1的试件即B1A1和B1C1,碳纤维或芳纶纤维先发生断裂;对于混杂比为2∶1的试件即B2A1和B2C1,玄武岩纤维先发生断裂.混杂片材的疲劳寿命随碳纤维或芳纶纤维含量的提高而提高,碳纤维含量的提高对其疲劳性能的影响更显著.B2A1的疲劳性能相对较差,B1C1和B2C1的疲劳性能相对较好.最后,提出一种新的双变量双拐点疲劳刚度退化模型,同时适用于多种纤维混杂片材和单种纤维片材.

关键词:混杂纤维增强复合材料片材;玄武岩-芳纶;玄武岩-碳;疲劳试验;刚度退化模型

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