J Wood Sci (2010) 56:154–159
DOI 10.1007/s10086-009-1084-7

ORIGINAL ARTICLE

Gökdeniz Neşer

Seawater exposure effect on the fracture toughness of low-density woods/GRP sandwich systems

Received: June 25, 2008 / Accepted: June 3, 2009 / Published online: January 29, 2010

Abstract The effect of seawater exposure on the fracture toughness of balsa (*Ochroma pyramidale* L.) and end-grain balsa cores that are widely used in small-craft constructive members has been investigated experimentally in this study. The interfacial fracture toughness was determined using mode I cracked sandwich beam (CSB) tests. Additionally, the same tests were performed for poplar (*Populus tremula* L.), easily available because of its natural distribution along the coast of Turkey and more cost-effective than balsa and its derivatives, to see if it is a proper alternative. It was found that balsa and poplar cores that can be classified as low-density cores have much lower fracture toughness values than end-grain balsa cores. Additionally, there was a positive effect of seawater exposure on their fracture toughness as opposed to that of the end-grain core. From the aspect of fracture toughness, the poplar core can be considered much more reliable than the balsa core where delamination loads occur.

Key words Environmental degradation · Wood/GRP sandwich systems · Fracture toughness · Mode I cracked sandwich beam test · Low-density woods

Introduction

In the early 1970s, boat designers realized that increasingly stiffer and lighter structures could be achieved if a sandwich construction technique were used. By laminating two face sheets, inner and outer, to low-density cores, highly reinforced parts are located at greater distances from the panel's neutral axis. These structures perform exceptionally well when subjected to bending loads produced by hydrodynamic forces. Lightweight sandwich structures offer many advantages compared to traditional stiffened panels, including high flexural rigidity and strength, ease of manufacture, improved stability and ease of repair.[1]

The performance of composite structures under prolonged immersion and exposure to wind, rain, and sun is generally good when compared with other usual construction materials.[2] Despite such characteristics, these materials suffer in some ways from a reduction of their original properties that, if not well understood and prevented, can lead to unexpected structural failures. These aspects should be carefully considered during the design process for a marine structure.[3]

Wood, as a hygroscopic material, will take up or release moisture depending on the temperature and relative humidity of the surrounding atmosphere. It is well known that changes in moisture content below the fiber saturation point strongly influence the mechanical properties of wood. Therefore, to understand wood fracture mechanical properties, the relationship between wood and its behavior under environmental effects must be considered.[4] Because of the relatively high density of most woods, only a few types are used for sandwich construction. The most popular low-density wood core material is balsa, but substantial use has also been made of spruce and cedar.[5]

The most important of structural failures of a sandwich system that occur during service is delamination that occurs either in the face–core interface or within the core material. Low-energy impact or manufacturing defects can result in separation of the face sheets from the core material. Under certain load and environmental conditions, these defects can grow and eventually cause the separation of the face sheet from the core. Mode I tests are essential in the proper design of such materials to improve the interlayer bonding, as well as the fracture toughness of the sandwich core material.[6]

Carlsson et al.[7] and Carlsson and Prasad[8] proposed several tests to investigate the mode I and mode II interfacial fracture toughness of sandwich materials. Cantwell and Davies[9] introduced the single cantilever beam, a modified version of mode I. For wood members reinforced with glass-reinforced plastics (GRP) plates, delamination of the composite between wood and GRP may occur because of

---

G. Neşer (✉)
Dokuz Eylül University Institute of Marine Sciences and Technology, Baku B. 10, Inciraltı, 35340 Izmir, Turkey
Tel. +90-232-278-5565; Fax +90-232-278-5082
e-mail: gokdeniz.neser@deu.edu.tr

high shear stress concentration. In this case, the fracture toughness under shear loading is a critical interface property for the evaluation of potential crack growth. Therefore, the opening mode I fracture is generally more critical and is recommended for qualification of bonded joints.[10]

The precise evaluation of fracture toughness in a composite system seems to be a difficult task because, apart from the complicated failure modes, certain experimental parameters also have a profound effect, such as the strain rate, temperature, and shape and size of the specimen.

The effect of the marine environment on the fracture toughness of balsa and end-grain balsa cores that are widely used in small-craft constructive members has been investigated experimentally in this study. The interfacial fracture toughness was determined using a mode I cracked sandwich beam (CSB) test. Additionally the same tests have been performed for poplar, easily available because it has a natural distribution along the coast of Turkey[11] and more cost-effective than balsa and its derivatives, to see if it is an appropriate alternative to them.

Experimental methods

Sample preparation

Poplar (*Populus tremula* L.) (core density = 336 kg/m^3), balsa (*Ochroma pyramidale* L.), and end-grain balsa (core density = 175 kg/m^3) were chosen as the study species. End-grain balsa is also known as a cross grain; this is a way of cutting balsa that involves cutting thin slices perpendicular to the run of the grain. The cross-grained pads thus obtained are used as core materials.

A typical CSB specimen on the test arrangement is shown in Fig. 1. Dimensions of the specimen are 305 mm in length, 40 mm in width, 15 mm in core thickness, and 2–3 mm in face thickness.

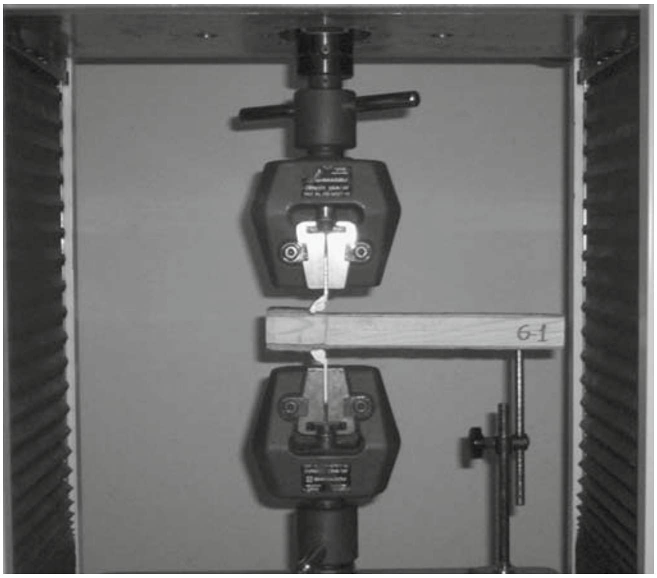

Fig. 1. Cracked sandwich beam (CSB) specimen and test arrangement

The face sheets in the species consisted of a GRP containing E-glass fiber fabrics (chopped strand mat, CSM) in an orthophthalic polyester resin (Dewester 196; Dewilux), which is widely used in boat building. The areal weights of CSMs were 300, 450, and 600 g/m^2. With the fabric of the face sheets, a face thickness of 2–3 mm was achieved. The weight fraction of glass of the face sheets was 34%.

Five CSB specimens for each sandwich system at each condition were machined because the aim of this work was to obtain a spectrum of results representing fracture behaviors in dry and wet conditions. After the CSB specimens were machined, the abraded surfaces of both the face and the hinge were cleaned with acetone and dried in air. Aluminum hinges were adhesively bonded by the same composite system to the top and bottom face sheets through which tension forces were applied to specimens. The hinges, which were mounted to a distance of 25 mm from one end, acted as load points for the CSB specimen.

To simulate a crack at the interface, an initial crack with a distance of 35 mm from one end was created, using a fine saw blade, into the interface region. Two sides parallel to the thickness directions of the specimens, which will be conditioned in salt-infused steam, were painted with epoxy-based paint to avoid water absorption through these sides.

Conditioning

The effect of seawater exposure on the interfacial fracture properties of materials was studied by conditioning with steam of a 5% solution of sodium chloride (NaCl) for a 120-h period at a constant temperature of 50°C in a conditioner at the mechanical laboratory of Turkish Standards Institution. Specimens were properly placed in the testing machine so as to be exposed to seawater from all directions homogeneously. The specimens, conditioned with salt-infused steam to accelerate aging in seawater, were allowed to dry in ambient temperatures until their humidity content dropped to the same values of 12% as the non-salt-treated specimens.

Experimental procedure

The specimens were tested on a Shimadzu universal testing machine. During the tests, specimens were supported against rotation and tested at a crosshead displacement rate of 4 mm/min according to ASTM D5528-01.[12] After a crack propagation of 3–5 mm, the specimens were unloaded at a high rate (maximum, 25 mm/min).

During the tests, crack propagations were monitored by a video camera. Specimens were loaded to a preindicated crosshead displacement, indicating a crack was observed, and then unloaded down to a load of 10 N. This test was continued until the specimens failed totally. Applied loads and crosshead displacements were recorded throughout the tests. It was observed that the load dropped as the crack grew in a steady fashion. Load and crosshead displacement were recorded throughout the test.

At the start of each test, the crack tip location was noted. The crosshead displacement was started and the crack tip was monitored from one side for growth. The crack was allowed to grow steadily until unsteady growth occurred. If the crack grew in a steady manner, the crack progression was monitored, and a flag was placed in the data file each time the crack tip passed through the intervals marked on the specimen. If the crack grew in an unsteady fashion, the crosshead displacement was stopped. The new crack tip location was found and noted. After locating the new crack tip, the crosshead displacement was reversed and unloading data were recorded. This procedure was repeated over approximately 200 mm of crack growth.

Interfacial fracture properties of the systems

The resistance to delamination growth can be characterized by the strain energy release rate (G), where the critical energy release rate (G_c) is used as a measure of the interlaminar fracture toughness.

The strain energy release rate was calculated from the load and displacement values obtained during the fracture tests using the area method. The energy released for a given crack extension is the area under the load–displacement curve. The area under a single load/unload cycle (ΔE) was calculated numerically using the trapezoidal rule. The trapezoidal rule works by approximating the region under the graph of a function by a trapezium and calculating its area. For one of the areas under the load–displacement curve (Fig. 2), ΔE_n can be calculated as follows by using the trapezoidal rule:

$$\Delta E_n = \Delta d \cdot \left(\frac{L_1 + L_2}{2}\right) + \Delta d.\left(\frac{L_2 + L_3}{2}\right) + \Delta d.\left(\frac{(L_3 - L_8) + (L_4 - L_7)}{2}\right) + \Delta d.\left(\frac{(L_5 - L_6) + (L_4 - L_7)}{2}\right) \tag{1}$$

$$\Delta E_n = \frac{\Delta d}{2} \cdot [(L_1 + 2L_2 + 2L_3 - L_8 + 2L_4 - 2L_7 + L_5 - L_6] \tag{2}$$

where Δd is interval and Ls is related load value.

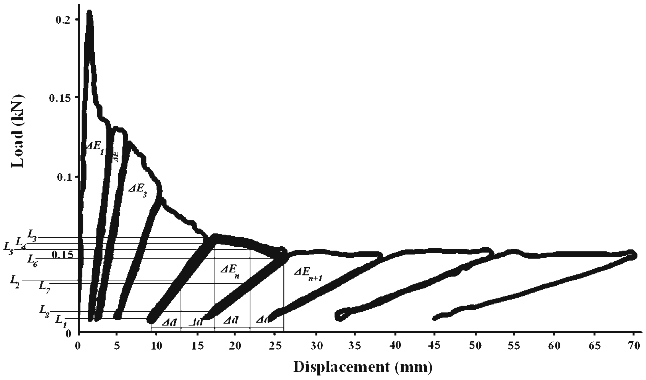

Fig. 2. Trapeziums for the areas method

Critical energy release rate, also defined as the fracture toughness, was obtained using the following expression:

$$G_c = \frac{1}{b} \cdot \frac{\Delta E}{\Delta a} \tag{3}$$

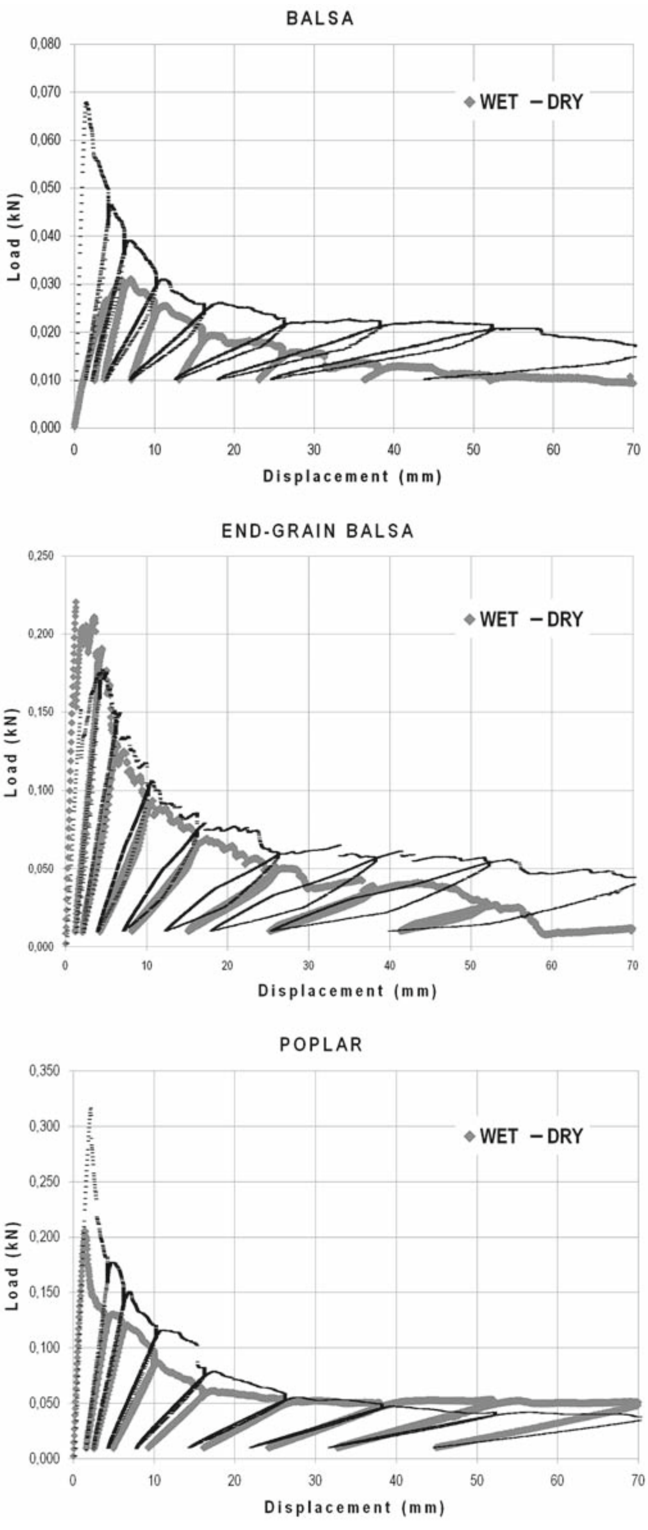

Fig. 3. Load–displacement curves of systems consequent to their core materials and testing condition

where ΔE is the area between known crack extension corresponding to the energy released as the crack grows, Δa is the crack extension noted during the test, and b the width of the specimen.

The value calculated is the average energy consumed for the crack extension Δa.

Results and discussion

Randomly selected examples of load–displacement curves for each of the low-density woods tested under dry and wet conditions are shown in Fig. 3. As the crack propagates, the

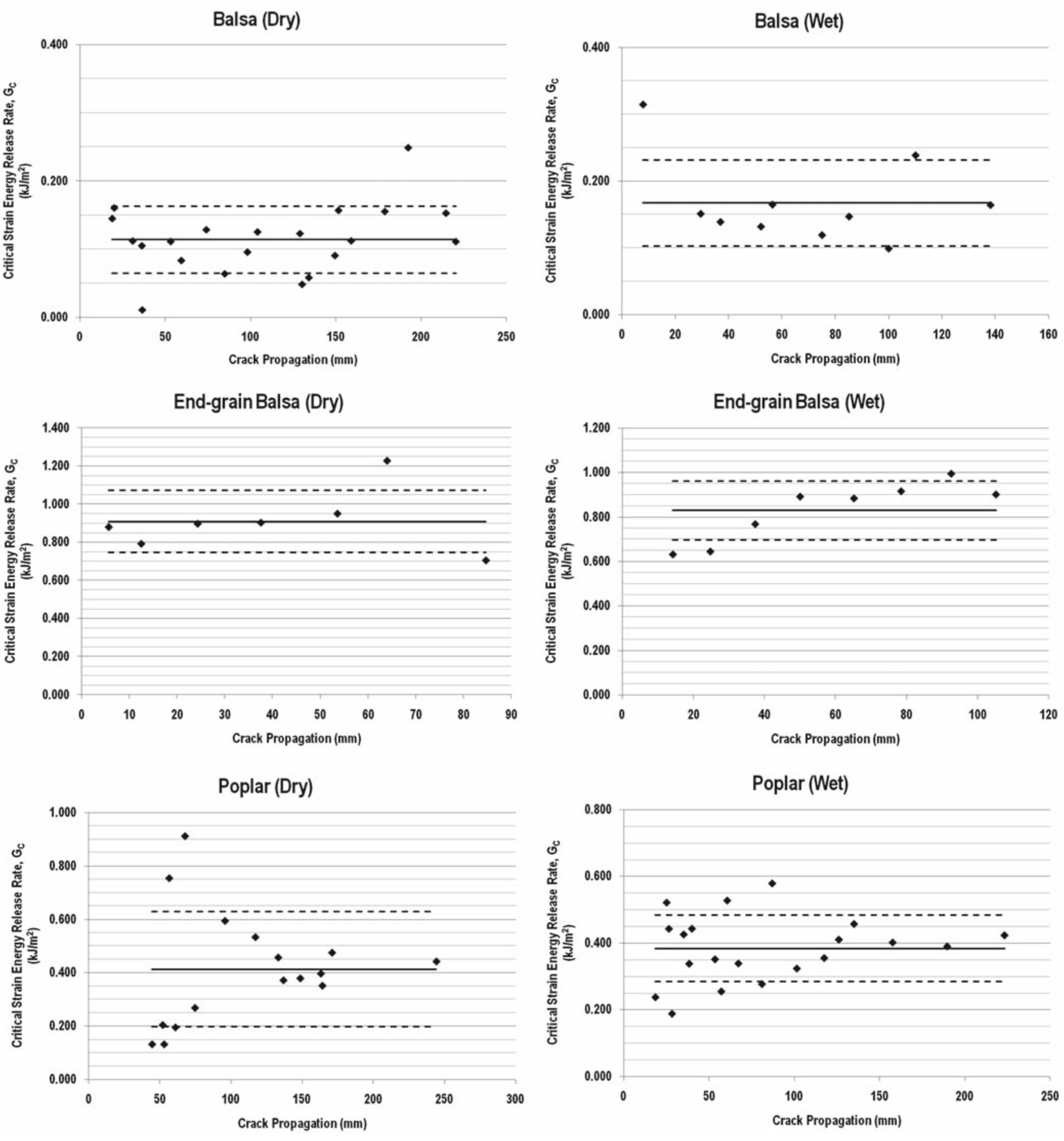

Fig. 4. Critical energy release rates of systems tested. ◆, G_C (area evaluation) ±1 SD

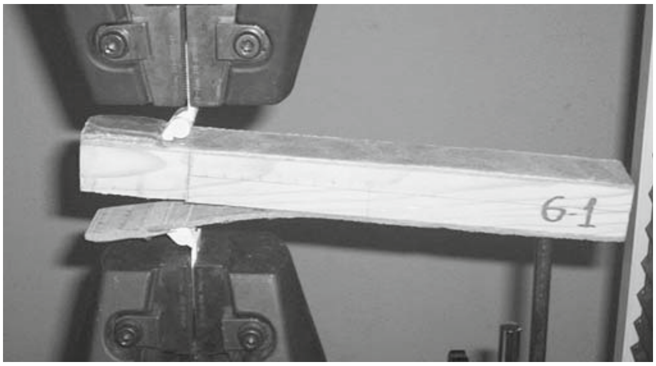

Fig. 5. A typical failure mode of the sandwich systems tested

load drops rapidly. This phenomenon can be observed from those curves. Mall et al.[13] found that the interlaminar fracture toughness decreases with increasing loading rate. As 4 mm/min was close to the maximum allowable rate in the aforementioned standard (5 mm/min), obtaining lower fracture toughness values from the tests would be expected.

The results of the area method outlined above were applied to the load–displacement curves, and the results obtained are shown in Fig. 4. Critical energy release rates (fracture toughness) versus crack propagation are indicated in this figure.

The roughness of the fracture surface of woods as a quasi-brittle material may be considered as potential source of toughening during crack propagation.[14] In this study, the effect of fracture surface roughness was considered as negligible because of lack of fiber bridging; a typical failure mode is shown in Fig. 5.

Conclusions

Experimental comparison of the interfacial fracture toughnesses of some sandwich systems consisting of GRP and low-density woods (balsa, end-grain balsa, and poplar) in two environments (atmospheric and immersion) has been studied by the mode I CSB test method.

The ratio of G_c (J/m^2)/d (kg/m^3) (fracture toughness/density) is 0.622 for the balsa core and 1.226 for the poplar core in the dry condition, and 0.948 for the balsa core and 1.450 for the poplar core after conditioning. Because achieving the lightest structure as possible is very important to the designers or builders of marine structures, poplar is not a preferable alternative to its counterparts. From the aspect of fracture toughness, the poplar core can be considered much more reliable than the balsa core where delamination loads occur.

By comparing the results obtained from tests performed for the systems of three different wood cores, it is concluded:

1. Fracture toughness of the system with end-grain balsa is higher compared with its counterparts. It has been considered that this system behaves as a single skin system. The system with end-grain balsa is followed by poplar and balsa.
2. Crack propagation seems to propagate right along the core–skin interface. It is believed that the reason for this propagation is that the strength of the subinterface is higher than the actual strength of the core–skin interface bonding.
3. From the studies by Cantwell et al.[15] and Scudamore and Cantwell,[2] it has been found that preconditioning with seawater has the effect of increasing fracture toughness of the system with the balsa core. Although the tests performed in this study confirm their findings, the same trend for poplar has been found. As for the end-grain core, a negative effect of seawater exposure on the core's fracture toughness has been shown.
4. Balsa and poplar cores that can be classified as low-density cores have much lower critical strain energy release rates than those of end-grain balsa cores. Additionally, there is a positive effect of seawater exposure on their fracture toughness as opposed to that of the end-grain core.

The induction of mode mixture was ignored in this study, considering the results of some previous research.[16,17] These studies reported that the effect of crack surface friction was considerable in the specimens that were used. As the fracture surface had no significant roughness and no fiber bridging was observed, only mode I fracture toughness has been discussed and used for comparison. However, because the G_c value of poplar is almost twice of the relative values in the literature[5] for a denser wood, fir (*Abies concolor* L.), from this phenomenon it can be concluded that these measured values were actually G_f, the nonlinear part of G_c. The higher values for conditioned woods may also be another clue that what was measured may be G_f.

Acknowledgments This research is supported by the Tacar Boat Company of Turkey. In addition, the author thanks Mr. Cemal Koçhan and the technicians of Dokuz Eylul University Engineering Faculty's Material Laboratory.

References

1. Saporito J (1989) Sandwich structures on Aerospatiale helicopters. In: Proceedings, 34th International SAMPE Symposium and Exhibition, Nevada, USA, pp 824–838
2. Scudamore RJ, Cantwell WJ (2002) The effect of moisture and loading rate on the interfacial fracture properties of sandwich structures. Polym Comp 23:406–417
3. Puccini G (1993) Environmental aspect. In: Shenoi RA, Wellicome JF (eds) Composite materials in marine structures, vol 1. Cambridge University Press, Cambridge
4. Liyu W, Thenyou L, Guangye Z (2003) Wood fracture pattern during the water absorption process. Holzforschung 57:639–643
5. Kolat K, Neser G, Ozes C (2007) The effect of sea water exposure on the interfacial fracture of some sandwich systems in marine use. Compos Struct 78:11–17
6. Papanicolaou GC, Bakos D (1996) Interlaminar fracture behaviour of sandwich structures. Compos Part A Appl S 27A:165–173
7. Carlsson LA, Sendlein LS, Merry SL (1991) Characterization of face sheet/core shear fracture of composite sandwich beams. J Compos Mater 25:101–116

8. Carlsson LA, Prasad S (1993) Interfacial fracture of sandwich beams. Eng Fract Mech 44:581–590
9. Cantwell WJ, Davies P (1994) A test technique for assessing core-skin adhesion in composite sandwich structures. J Mater Sci Lett 13:203–205
10. Wang J, Qiao P (2003) Fracture toughness of wood–wood and wood–FRP bonded interfaces under mode-II loading. J Compos Mater 37:875–897
11. Oner N, Aslan S (2002) Technological properties and possible uses of trembling poplar (*Populus tremula* L.) wood. Suleyman Demirel Univ Bull Fac For 1:135–146
12. The American Society for Testing and Materials (ASTM) (2007) ASTM Standard D5528-01: standard test method for mode I interlaminar fracture toughness of unidirectional fiber-reinforced polymer matrix composites. ASTM, Conshohocken, PA
13. Mall S, Law GE, Smith ST (1997) Loading rate effect on interlaminar fracture toughness of a thermoplastic composite. J Compos Mater 21:569–579
14. Morel S, Mourot G, Schmittbuhl J (2003) Influence of the specimen geometry on R-curve behavior and roughening of fracture surface. Int J Fract 121:23–42
15. Cantwell WJ, Scudamore R, Ratcliffe J, Davies P (1999) Interfacial fracture in sandwich laminates. Compos Sci Technol 59:2079–2085
16. Tan DM, Stanzl-Tschegg SE, Tschegg EK (1995) Models of wood fracture in mode I and mode II. Holz Roh-Werkstoff 53:159–164
17. Jernskvist LO (2001) Fracture of wood under mixed mode loading II. Experimental investigation of *Picea abies*. Eng Fract Mech 68:565–576