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Buckling Resistance of Basalt Fiber Reinforced Polymer Infill Panel Subjected to Elevated Temperatures

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***Abstract*—**Performance of Basalt Fiber Reinforced Polymer (BFRP) sandwich infill panel system under diagonal compression was studied by means of numerical analysis. Furthermore, the variation of temperature was considered to affect the mechanical properties of BFRP, since their composition was based on polymeric material. Moreover, commercial finite element analysis platform ABAQUS was used to model and analyze this infill panel system. Consequently, results of the analyses show that the overall performance of BFRP panel had a 15% increase compared to that of GFRP infill panel system. However, the variation of buckling load in terms of temperature for the BFRP system showed a more sensitive nature compared to those of GFRP system.

***Keywords*—**Basalt Fiber Reinforced Polymer, Buckling performance, numerical simulation, temperature dependent materials.

I. Introduction

FRAMED buildings with infilling walls are a type of structural system that provides lateral load resistance and lateral stiffness. Uncertain and complex interaction of series of infilling frames has led the real composite behavior of the structure to be considered as a statistically indeterminate problem. Extended as early as the 1950’s and continuing to date, available literature attempts to provide several efficient approaches in the field of analysis and design of infilled frames. Saneinejad and Hobb and Jung-Min and Myung-Ho [1], [2] proposed a method of transforming the infilled frames into equivalent diagonal strut bracing frames. The studies stress that mutual interactions of the frame and infills panel play an important part in controlling the strength and stiffness of infilled frames. It was shown by Jung and Aref [3] that for equivalent diagonal strut model, diagonal stiffness and strength of the infill panels depend primarily on their dimensions, physical properties and length of contact with the surrounding structural frames. However, it should be noted that modeling of frame/infill contact lengths with exact mathematical solution is a complex issue involving several factors and a high degree of uncertainty. Indeed, under seismic loads, the failure generally occurs at either frames or the infill panels due to the tension failure of the columns or shearing of the columns or beams which are critical modes of frame failure depending on several factors. It may occur in infilled frames as racking load increases, if the strength of the frame is sufficient to prevent collapse by one of these modes. A published work by Aref and Jung [4] indicated that Polymer Matrix Composite (PMC) materials could be utilized in a new efficient conceptual designs for seismic retrofitting in existing facilities. Due to its high stiffness-to-weight and strength-to-weight ratios, the addition of PMC infill panels into existing structures will not significantly alter the weight of the structure while providing substantial structural enhancement.

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Recently, basalt fiber (BF) has been emerging as a new type of reinforcing material of PMC due to its unique mechanical, thermal and chemical properties. BF was first mentioned by Subramanian and Austin [6], who reported that it could be applied to composites that include polypropylene (PP) as the matrix where it can be used widely in many applications comparable to Glass fiber-reinforced polymer (GFRP). Basalt’s most important chemical compositions (SiO_2, Al_2O_3, CaO, MgO, Fe_2O_3 and FeO) and its high molten temperature (between 1350 ºC and 1700 ºC) allow BF to be used between -200 ºC and 600 ºC without significant loss of mechanical properties. However, BFRP has viscoelastic properties where the effect of temperature for their design as infill panels is important to the function of components and assemblies when operating in different environments. Hence, in civil engineering applications where controlled thermal expansion characteristics are required, it is essential to evaluate BFRP for their thermal stability. Several studies mentioned the enhancement of performance with respect to thermal stability, dynamic viscoelasticity and mechanical properties of BFRP when exposed to various temperatures [7]-[9]. From the literature review, only limited investigations have been carried out on the basis of BFRP. In addition to this influence, in the previous study, Jung and Aref also reveal that the failure of global buckling is dominant when designing the PMC infill panel in certain stacking sequences. Therefore, the objective of this study was to investigate the performance of BFRP infill panel where the optimal stacking sequence and other parameters from the previous study [3]-[5] will be used. Moreover, the sensitivity to temperature variation ranging from -20 °C to 60 °C on the buckling response of an infill panel system will be evaluated and compared with those found in a GFRP infill panel system. Finite element model will be made with ABAQUS platform [10], to determine the critical buckling load.

II. Description and Mechanism of PMC Infill Panel

For the design process, PMC infill wall system is fabricated as a composite sandwich structure consists of two thin FRP laminates (skin) separated by a thick infill of foam (core). The resultant structures shown in Fig. 1 are a composite system having lightweight, high strength and stiffness characteristics. In the case of the study presented here, polystyrene was used as the core materials and laminate of BFRP was used as the skin materials. The specifications of the design are as follows: thickness values of skin and core are 6 mm and 20 mm, respectively, resulted in a total thickness of 32 mm and overall dimension of 2200 mm by 2400 mm. The optimization of the design stacking sequences of skin laminate was chosen based on the result of previous design with a general orthotropic fiber-orientation distribution [45_5/-45_{10}/45_{10}/-45_{10}/45_5/ core /45_5/-45_{10}/45_{10}/-45_{10}/45_5], where subscript represents the number of lamina in each fiber-orientation.

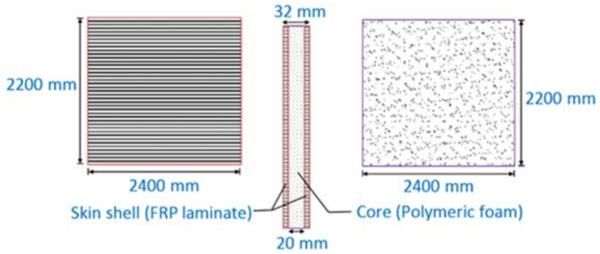

Fig. 1 Configuration and dimension of BFRP infill panel system

Additionally, Table I presents the mechanical properties of foam core and BFRP skin. Only four constants needed to describe the in-plane behavior of thin laminae. Analytical method provides a reasonable way to determine these constants by a relatively simple "rule of mixture", for the first modulus along the fiber direction. However, this method was based on the assumption that the BF and epoxy matrix shall deform in equal amounts along the fiber direction [11], [12]. Relying on the well-known accuracy of this assumption, we could accurately estimate the apparent elastic modulus E_1 with:

$$E_1 = E_f V_f + E_m V_m \tag{1}$$

where E_f is the fiber modulus, V_f is the fiber volume fraction, E_m is the matrix modulus, and $V_m = 1\text{-}V_f$.

One simplifying assumption can be made considering the stress σ_2 in the fiber and matrix in order to determine the second modulus along the transverse direction. Halpin-Tsai equation [13] is a set of empirical relations which enables elastic modulus E_2 to be expressed as:

$$\frac{E_2}{E_m} = \frac{1+\xi\eta V_f}{1-\eta V_f} \tag{2}$$

$$\eta = \frac{E_f/E_m - 1}{E_f/E_m + \xi} \tag{3}$$

where ξ is a reinforcement parameter depending on the loading and boundary condition of the fiber geometry. The suitable value of an empirical factor ξ which has been observed to yield accurate results is permitted to be taken as 1.

Resulting from the previous two assumptions of having the fiber and the matrix deform in equal amounts along the fiber direction and having the transverse stress $\sigma_2 = 0$, according to the rule of mixtures, properties of composite materials, Poisson's ratio v_{12}, can be estimated as [11]:

$$v_{12} = v_f V_f + v_m V_m \tag{4}$$

where v_f is the fiber Poisson's ratio and v_m is the matrix Poisson's ratio. The assumptions are known to be accurate, leading to an accurate estimation of the major Poisson's ratio v_{12}.

In the strength of material approach, the determination of shear modulus G_{12} was based on the Halpin-Tsai equation along with the assumption that the shearing stress of the fiber and the matrix are identical:

$$\frac{G_{12}}{G_m} = \frac{1+\xi\eta V_f}{1-\eta V_f} \tag{5}$$

$$\eta = \frac{G_f/G_m - 1}{G_f/G_m + \xi} \tag{6}$$

where $\xi = 1$ as in (3). Consequently, the four constants (E_1, E_2, v_{12} and G_{12}) could be obtained based on BF and epoxy properties at each temperature and will be used in FE model of the infill panel system to derive the buckling performance of infill panel in function of temperature.

TABLE I
Mechanical Properties of Polystyrene and BFRP Lamina

Temp.	Polystyrene		BFRP Lamina			
[˚C]	E [MPa]	ν	E_1 [GPa]	E_2 [GPa]	v_{12}	G_{12} [GPa]
-20	130.7	0.33	55.50	17.28	0.27	6.45
0	125.4	0.33	55.34	16.15	0.27	6.02
20	120.0	0.33	54.99	13.71	0.27	5.09
40	113.9	0.33	54.71	11.59	0.27	4.30
60	110.9	0.33	54.38	8.957	0.27	3.31

III. Numerical Modeling and Analysis

Evaluation of the buckling performance of an infill panel was performed by developing finite element (FE) model in ABAQUS platform; however, the model was simplified by modeling only the infill panel without the surrounding frames. This assumption was found to be adequate since the contact between infill and frame will be modeled by contact length, as shown in Fig. 2. The core layer was modeled with three-dimensional solid elements (C3D8); and skin plates were modeled by composite layup of BFRP lamina sheets and discretized with quadrilateral shell elements (S4R5).

Fig. 2 demonstrates the triangular distributed compression loads which were applied along the length of contact between columns and infills ($\alpha_c h'$) to achieve the in-plane compression design of the infill. In this case, two translational degrees of freedoms along *Y*- and *Z*-direction and a rotational degree of freedom for *Z*-direction were constrained for modeling contacts between beams and infills ($\alpha_b l'$). This length of contact was taken to be 500 mm.

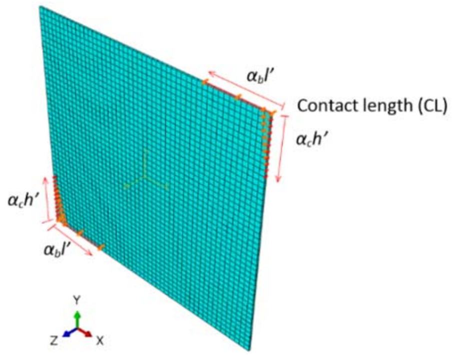

Fig. 2 FE model of PMC sandwich infill panel

IV. Results and Discussions

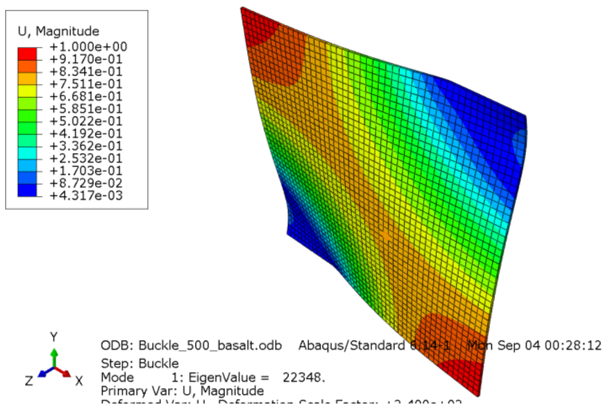

Fig. 3 Failure shape of infill panel system

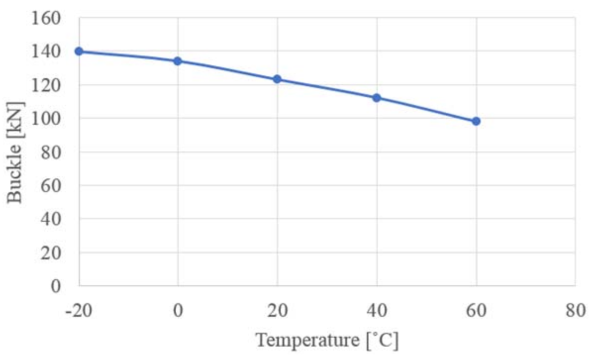

Fig. 4 Buckling load in term of temperature

The buckling failure shape of BFRP infill panel was shown in Fig. 3. In this figure, the buckling of infill occurs as the compression load reaches a critical value of 123 kN. This load can be determined by multiplying the eigenvalue of the failure mode shape, i.e. 22348, with the applied load along the contact length between beam and infill panel. This loading can be considered as unit load for buckling analysis, which is the most basic form of buckling analysis in FEA. Additionally, Fig. 4 shows the performance of BFRP infill panel system in function of temperature ranging from -20°C to 60°C. It is observed that as the temperature increases, the performance of infill panel decreases; this is due to the polymeric properties of their material compositions. Furthermore, analysis of this curve shows that the decrement rate of buckling performance was 0.4% per degree Celsius. This decrement rate is the normalized value of load decrease in comparison with the maximum buckling load over the total range of 80°C. In consequence, this result shows a larger value compared to the decrement rate of the GFRP infill panel system found in the previous study of [5]; this means that infill panels with BFRP as a skin layer are more sensitive to temperature variation than those with skin comprised of GFRP. However, the overall performance of the BFRP infill panel system shows a higher resistance capacity; the average increase from the GFRP infill panel system was found to be about 15% over the entire range of temperature. This increment owed to the higher Young's modulus of BF. Thus, with the same fraction of fiber in the composite lamina sheet, which make up the laminate skin layer, BFRP laminate will have a better performance compared to GFRP.

V. Conclusions

This paper showed the determination of critical load which causes the buckling of a BFRP infill panel system. Furthermore, buckling load was calculated by means of finite element modeling with a commercial finite element analysis platform ABAQUS. Additionally, the variation of temperature, which affects the mechanical properties of the BFRP infill panel system composition, has also been considered in the FE model of the infill panel system.

Results from the modeling and analysis show that the performance of the BFRP infill panel system has a tendency to decrease as the temperature rises. The decrease in performance of this infill panel system was found to be around 0.4% per degree Celsius. This result shows a higher value compare to those found in GFRP infill panel system. However, for the overall performance of BFRP infill panel system, it shows a better result; there is a 15% increase in buckling load compared to the GFRP system.

Acknowledgment

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