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Comparison of PMC Infills Compressive Strength Performance under Laminate Orientation and Temperature Effect

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Abstract: Polymer-Matrix Composites (PMC) are a major evolution for energy dissipation when used as infill materials for seismic retrofitting of steel frames; however, they are viscoelastic materials and their mechanical properties are considerably influenced by temperature. The present study intended to investigate the effect of temperature on buckling failure of laminated Fiber-Reinforced Polymer (FRP) sandwich infill panels under in-plane compression. Mode of failure under in-plane compression was studied by means of numerical analysis with ABAQUS platform. Three different types of composite laminates have been employed for skin plates. The effect of fiber-orientation angles on the buckling of PMC infills was studied with four cases of simple stacking sequences. As well as contact length between frames and infill. Results showed that buckling resistance was proportional with contact length and inversely proportional with temperature variation. Furthermore, the laminate stiffness could be modified by orientation of fiber in laminates which could increase the infill panels strength. Among the three materials studied, CFRP showed the most superior properties.

Key words: Compressive resistance, GFRP, CFRP, AFRP infill, stacking sequence, temperature dependent

INTRODUCTION

The significance of infilling walls in determining the actual strength and stiffness of framed buildings subjected to lateral force has long been recognized. They can provide significant lateral strength. However, the combined behavior of a series of infill frame structures is a complex, statically indeterminate problem. Attempts at the analysis and design of infilled frames since the mid-1950s have led to several methods. One interesting method proposed by Saneinejad and Hobbs (1995) and Jung and Myung (2016) was to transform the infilled frames into equivalent diagonal strut bracing frames. The mutual interactions of the frames and infill panels play an important part in controlling the stiffness and strength of the infilled frames. For diagonally equivalent strut model, Jung and Aref (2005) show that the diagonal stiffness and strength of the infill panels depend primarily on their dimensions, physical properties and length of contact with the surrounding structural frames. Development of an exact mathematical solution for frame/infill contact lengths may be possible but rather complicated, involving perhaps a trial-and-error procedure.

During earthquake as the racking load increased on infill frame structures, failure occurs eventually at either the frames or the infill panels. The critical modes of frame failure are tension in the columns or shearing of the columns or beams. However, if strength of frame is sufficient to prevent its collapse by one of these modes, the increasing racking load eventually produces compressive failure in the infill panels.

By using Polymer Matrix Composite (PMC) materials, new conceptual designs for seismic retrofitting were developed for application in existing buildings by Aref and Jung (2003). The use of prefabricated PMC infill panel systems is a very efficient way to achieve seismic retrofitting of existing facilities because of the efficiency of material and its ease of use in construction. PMC material has high stiffness-to-weight and strength-to-weight ratios. Thus, the addition of PMC infill panels into existing structures will not significantly alter the weight of the structure while providing substantial structural enhancement. The failure modes of sandwich PMC infill panel can be generally classified into three categories: instabilities such as overall buckling, face wrinkling, caused by insufficient plate-or face-bending stiffness and core elastic properties and fracture, either of the face sheets under compression or of the core under transverse shear. The research performed by Jung and Aref reveals that the failure of global buckling is dominant when designing the PMC infill panel. The results highlight the key roles of the PMC laminate skin and influence of stacking sequence on its performance. Although, PMC panel is viscoelastic material, the effect of temperature has

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rarely been addressed for their design as infill panels. The thermal properties of polymeric materials are important to the function of components and assemblies that will operate in different environments. In previous study buckling response of infill panel systems under the influence of temperature and stacking sequences of FRP laminae was studied (Sim *et al*., 2016; Lee *et al*., 2016).

Hence, this study will compare buckling resistance performances under temperature variation of PMC infill panels when skin plates were made of different types of composite laminates. Three widely used composite laminates, Glass Fiber-Reinforced Polymer (GFRP), Carbon Fiber-Feinforced Polymer (CFRP) and Aramid Fiber-Reinforced Polymer (AFRP) were being considered. Then, the effect of fiber-orientation angles (stacking sequences) on the buckling strength of the system and sensitivity to temperature variation could be compared when four different cases of stacking sequences were applied for skin.

MATERIALS AND METHODS

Configuration and properties of PMC infill panel: Figure 1 shows the cyclic lateral loading experimental set-up of infilled frame structure. In this figure, a PMC panel surrounded by steel frames and horizontal loading on the upper beam was applied. Loads transferred to PMC infill through connection on the upper and lower beam. A basic PMC infill wall system consists of two FRP laminates (skin) surrounding an infill of foam (core). Figure 2 shows configuration and dimensions of a PMC infill panel which consisted of 20 mm core and two 6 mm skin plates with a height and width of 2200 and 2400 mm, respectively. Properties of core and FRP laminae are shown in Table 1 (Mott *et al*., 2008; Kelly and Zweben, 2000; Roylance, 2000; Reed and Golda, 1994; Mivehchi and Varvani-Farahani (2010). The numerical analysis referred to laminate skins with constant thickness and was performed by varying fiber orientation in laminates (stacking sequences) of the FRP skin layer. Four cases of simple stacking sequences (Jones, 1975) were considered in the present analysis and the lay-up cross section and fiber-orientation of each is listed in brackets following:

- Case 1-isotropic layers: (040/core/040)
- Case 2-special orthotropic layers: (05/9010/010/9010/05/core/05/9010/010/9010/05)
- Case 3-general orthotropic layers: (455/-4510/4510/-4510/455/core/455/-4510/4510/-4510/455)
- Case 4-multiple anisotropic layers: (05/455/-455/9010/-455/455/05/core/05/455/-455/9010/-455/455/05)

Fig. 1: Experiment set-up of PMC infill

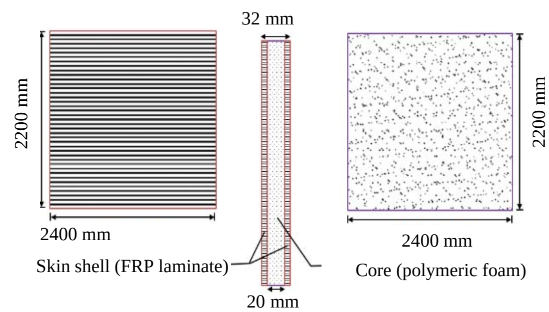

Fig. 2: Configuration of the PMC infill panel

Numerical analysis of the panel: In order to identify the buckling performances of PMC infill panel, Finite Element (FE) model of infill panel, without the surrounding frames, was developed in ABAQUS. The core sheet layer was modeled with three-dimensional solid elements (C3D8). The skin plates were modeled by composite layup of FRP lamina sheets followed the four cases and discretized with quadrilateral shell elements (S4R5). A tie constraint was introduced between the nodes of the shell elements and the solid elements. Material properties used for this analysis are given in Table 1. The contacts between beams and infills were modeled constraining translationaldegrees of free for both y and z-direction and rotational degree of freedom for z-direction along the length of contact for both the top and bottom beams as demonstrates in Fig. 3. Triangular distributed compression loads were applied along the length of contact against the columns.

A series of buckling analysis of the PMC infill panel were conducted to evaluate their buckling resistance for each case of stacking sequences and different type of skin laminates material. Temperature variation altered their mechanical properties.

Table 1: Mechanical properties of core and PMC skin at -20°-60°C

Temperature (°C)	Factors	-20	0	20	40	60
Core						
Polystyrene	E [MPa]	130.70	125.40	120.00	113.90	110.90
	ν	0.33	0.33	0.33	0.33	0.33
Glass fiber	E_1 [GPa]	58.30	57.80	57.00	56.30	55.30
Reinforced	E_2 [GPa]	16.40	16.20	16.00	15.80	15.50
Polymer	ν_{12}	0.26	0.26	0.26	0.26	0.26
	G_{12} [GPa]	7.80	7.70	7.60	7.50	7.40
Skin						
Carbon	E_1 [GPa]	136.10	134.80	133.00	131.30	128.90
Fiber	E_2 [GPa]	6.80	6.70	6.60	6.50	6.40
Reinforced	ν_{12}	0.25	0.25	0.25	0.25	0.25
Polymer	G_{12} [GPa]	4.90	4.90	4.80	4.70	4.70
Aramid fiber	E_1 [GPa]	85.20	83.00	80.00	77.20	73.10
Reinforced	E_2 [GPa]	5.90	5.70	5.50	5.30	5.00
Polymer	ν_{12}	0.31	0.31	0.31	0.31	0.31
	G_{12} [GPa]	2.20	2.20	2.10	2.00	1.90

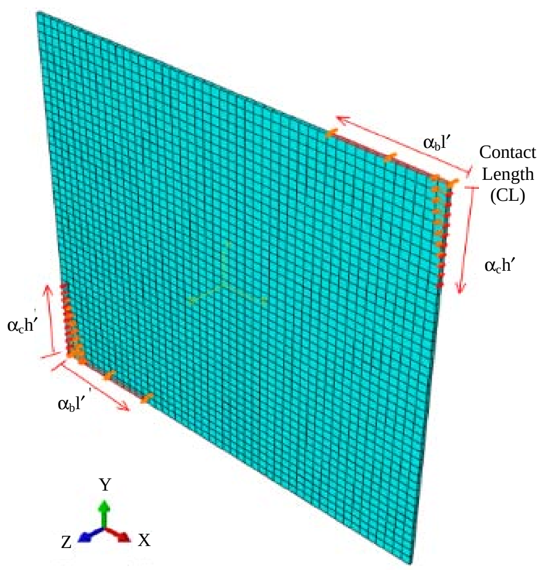

Fig. 3: FE model of the infill panel in ABAQUS

RESULTS AND DISCUSSION

Failure mode of panel system: Under lateral loading, predominate buckling mode shape of infill panel system is shown in Fig. 4. Eigenvalue, also known as load multiplier, was extracted. By multiplying eigenvalue with the applied load, the most likely load to cause buckling of the panel was obtained. This value was the buckling resistance of the infill panel. Results obtained after this analysis is shown in Table 2.

Effect of stacking sequence: Simply through the rearrangement of stacking sequence, a large gap of fiber orientation angle's effect on buckling strength can be clearly observing in Fig. 5. By orienting the fiber in general orthotropic layers and multiple anisotropic layers, Case 3 and 4, respectively, the buckling resistances greatly increased for all three types of FRP. This specific orientation provided in Case 3 offers the best direction that can benefit from stiffening properties against buckling which equivalently resulted in the reinforcement of the overall panel structure. This orienting laminae's sequence into specific orientation led to the modification of strength and stiffness of panel to go against the critical buckling direction. This proved the significance of the effect of stacking sequence for design factor.

Effect of temperature variation: Figure 6, a plot of buckling resistances versus temperature, introduces the effect of temperature on buckling performances for all three types of skin laminates. This figure expresses the result when using Case 3 of stacking sequence. As the temperature increased the buckling strength of panel decreased. Other cases of stacking sequences showed similar trend except with different slope of decrement.

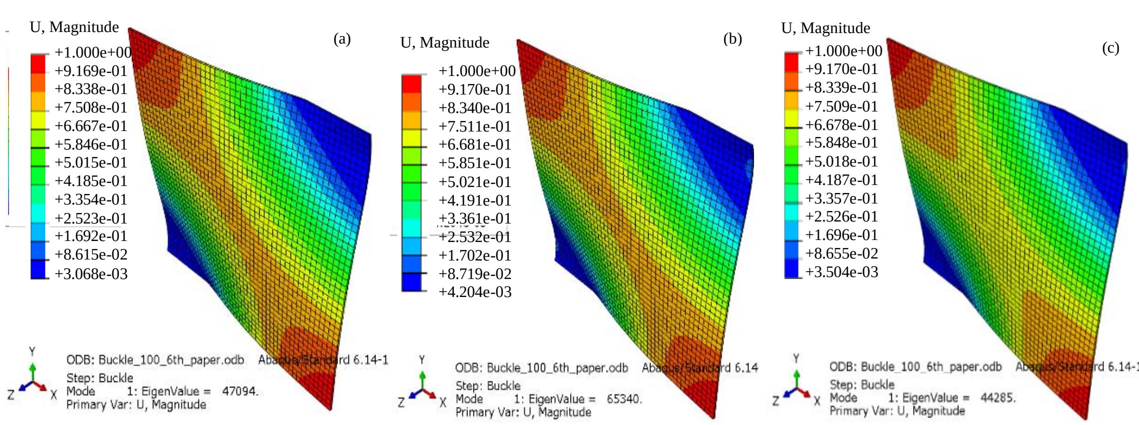

Fig. 4: Buckling failure of: a) GFRP; b) CFRP and c) AFRP infill

Table 2: Buckling performance of GFRP, CFRP and AFRP infill

	Temperature (°C)														
	GFRP					CFRP					AFRP				
CL	-20	0	20	40	60	-20	0	20	40	60	-20	0	20	40	60
Case 1															
100	52.4	51.5	50.4	49.2	48.2	30.5	30.0	29.5	28.8	28.3	22.4	21.7	20.8	20.0	19.0
200	62.6	61.5	60.1	58.7	57.5	36.6	36.0	35.3	34.6	33.9	26.8	26.0	25.0	24.0	22.8
300	68.7	67.4	65.9	64.3	63.0	40.4	39.7	38.9	38.1	37.3	29.5	28.6	27.5	26.4	25.2
400	73.1	71.7	70.1	68.4	67.1	43.2	42.5	41.6	40.8	39.9	31.6	30.6	29.4	28.3	26.9
500	76.8	75.4	73.7	71.9	70.5	45.7	44.9	44.0	43.1	42.2	33.3	32.3	31.1	29.8	28.4
Case 2															
100	66.1	64.8	63.3	61.6	60.3	66.8	65.4	63.8	62.1	60.8	42.7	41.4	39.7	38.1	36.3
200	78.8	77.2	75.4	73.4	71.9	79.8	78.2	76.3	74.2	72.7	51.1	49.5	47.5	45.6	43.4
300	86.0	84.3	82.3	80.2	78.5	87.6	85.7	83.7	81.4	79.7	56.2	54.4	52.2	50.1	47.7
400	91.0	89.2	87.1	84.8	83.1	93.1	91.1	88.9	86.5	84.7	59.9	58.0	55.7	53.3	50.9
500	95.1	93.1	90.9	88.5	86.7	97.6	95.5	93.2	90.7	88.7	62.9	60.9	58.5	56.1	53.5
Case 3															
100	83.8	82.1	80.1	77.9	76.3	118.2	115.5	112.5	109.1	106.8	84.3	81.6	78.3	75.0	71.5
200	99.6	97.5	95.2	92.6	90.7	140.3	137.2	133.6	129.6	126.9	100.0	96.8	92.8	88.9	84.8
300	108.4	106.1	103.6	100.8	98.7	152.6	149.2	145.3	141.0	138.0	108.6	105.1	100.8	96.6	92.2
400	114.3	111.9	109.2	106.3	104.1	160.9	157.3	153.2	148.8	145.6	114.5	110.8	106.3	101.8	97.1
500	119.0	116.6	113.7	110.6	108.3	167.6	163.8	159.6	155.0	151.7	119.2	115.4	110.7	106.0	101.1
Case 4															
100	77.5	75.9	74.1	72.1	70.6	108.5	106.0	103.2	100.2	98.0	78.3	75.8	72.7	69.6	66.4
200	92.2	90.3	88.1	85.7	84.0	128.7	125.7	122.4	118.7	116.2	92.9	89.9	86.2	82.5	78.8
300	100.4	98.3	95.9	93.3	91.4	139.7	136.5	132.9	128.9	126.1	101.0	97.7	93.7	89.7	85.6
400	106.0	103.8	101.3	98.5	96.5	147.2	143.8	140.0	135.8	132.9	106.5	103.1	98.8	94.6	90.3
500	110.4	108.1	105.5	102.6	100.5	153.4	149.8	145.8	141.4	138.4	111.0	107.4	103.0	98.5	94.1

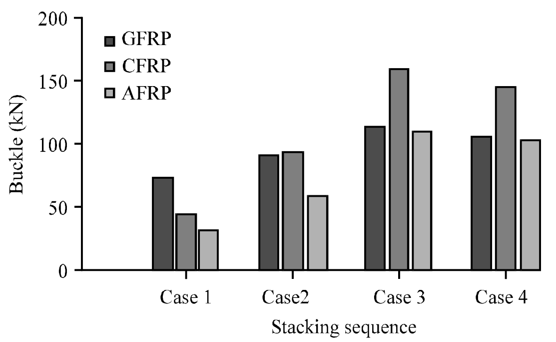

Fig. 5: The effect of stacking sequence on buckling resistance

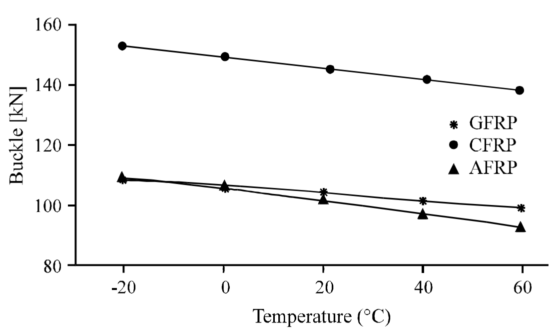

Fig. 6: Buckling resistance in function of temperature

CFRP showed the highest buckling resistance, this is due to their higher elastic modulus (with the same fiber volume

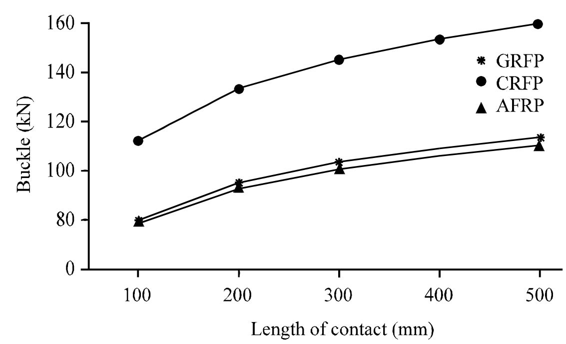

Fig. 7: Buckling resistance in function of contact length

as GFRP and AFRP). CFRP is a costlier material than its counterparts, GFRP and AFRP in the construction industry, though CFRP is in general, regarded as having superior properties.

Effect of contact length: Figure 7 shows a plot of buckling resistances v/s contact length at temperature 20°C. The buckling strength increased proportionally to the contact lengths. However, unlike in term of temperature, slope of the curve was not linear.

Combining curves in Fig. 6 and 7, a surface plot of buckling resistances in function of contact lengths and temperature could be obtained in Fig. 8. There was an upward displacement of curve's surface as contact length increased and temperature decreased. Therefore, a more quantitative form is shown in Fig. 9, a plot of decrement percentage of buckling resistances for each

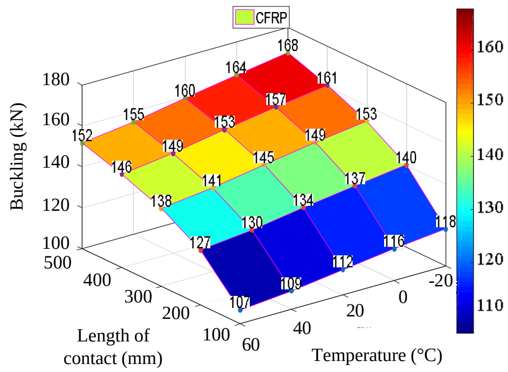

Fig. 8: Buckling resistance in function of contact length

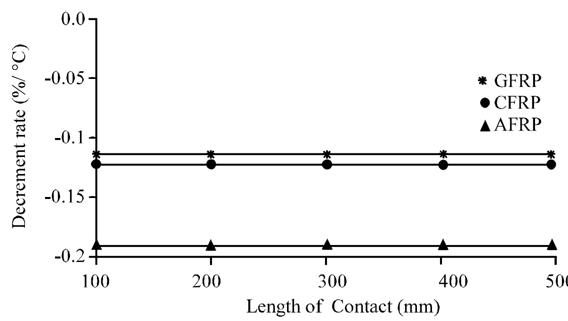

Fig. 9: Comparison of decreasing percentage of buckling resistance

laminate materials v/s contact lengths. This curve shows normalizing values of buckling resistance decrement rate per 1°C over the maximum buckling resistance. GFRP and CFRP showed similar value 0.1% which just half of AFRP, 0.2%. This results shows that when GFRP and CFRP were being used as skin plate laminates, buckling strength of PMC infill panel was less sensitive to temperature variation.

CONCLUSION

Numerical study of PMC infill panel's buckling resistance was conducted by considering the influence of temperature variation. Three different types of fiber materials for skin plates and four different stacking sequences of composite laminates were being used for PMC infill panels. Increment of temperature decreased the performance of the panels this was due to their polymeric nature. Furthermore, the buckling resistance increase proportionally with the contact length this was caused by the widening of strut width of the diagonally equivalent strut model. In term of stacking sequences, Case 3 proved to be preeminent compares to other cases for both its higher performance and lower sensitivity to effect of temperature variation. Additionally, CFRP proved to be the most superior for both performance and temperature sensitivity. However in the construction industry CFRP is costlier material than its counterparts, GFRP and AFRP. In this research, four simple cases of stacking sequences were used for the focus of exploratory and not performance-based, many other choices of stacking sequences were yet to be explored in order to determine an optimized option which can lead to higher performance and less sensitive to variation of temperature. Nonetheless, this research has developed a trend which serves as a framework for further study to determine optimal stacking sequence and considering other design parameters.

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