THE EFFECT OF WEAVE STACKING ON MODE I FRACTURE TOUGHNESS OF COMPOSITES

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ABSTRACT

It is well-known that composite laminates including woven composites offer high specific modulus and strength, but their interlaminar strength is relatively weak. This study investigated the effect of stacking configuration of woven composites on their resistance to Mode I peel loading, or so called Mode I fracture toughness, G_I, of composite. The test results of double cantilever beam experiments showed that G_I can vary by more than 10% due to the alignment of fabric layers. G_I increases with the amount of 0°/90° and 90°/90° yarn contact interfaces and reduces with as the amount of 0°/0° yarn contact interfaces. Since precise alignment of fabric layers is not easy to achieve in an industrial environment, an analytical contact analysis was performed to identify the effect of fabric alignment on Mode I fracture toughness. Such alignment include a combination of translation, rotation and turn over for orthogonal stacking of fabric layers,. The analysis showed that balanced weaves are less affected by the alignment of fabric layers while weaves featuring highly unbalanced interlacing could achieve greater coverage of high G_I contact interfaces.

1 INTRODUCTION

The fracture behaviour under Mode I loading of polymer matrix composites (PMCs) reinforced with weaves is much more complex than that of unidirectional PMCs. In general, the use of weaves provides greater Mode I interlaminar fracture toughness, G_I, compared with the use of unidirectional fibre reinforcements [1–3]. However, G_I varies locally within weaves which gives rise to unstable delamination [1, 4–7].

G_I of woven PMCs is affected by the weave construction. Interlacing creates resin rich zone that can affect G_I [1, 2], favourably or not depending on the toughness of the resin matrix. In addition, Alif et al. [10] tested plain weave, twill and 5-harness glass PMCs and observed that lower levels of interlacing increased fibre bridging and G_I. Conversely, in other studies [2–5, 9] the interlacing of yarns increased the surface roughness of the delamination interface which increased G_I. Studies [8, 11] found that an increase in yarn width increases fibre bridging and G_I.

G_I of woven PMCs is also affected significantly by the stacking configuration of woven layers [8, 11]. Configurations that provide greater 0°/0° yarn contact result in lower G_I interfaces. Therefore, investigation of the stacking configurations is critical for identifying the optimal alignment between fabric layers. In non-laboratory conditions, precise alignment of fabric layers is not realistic due to time and technical constraints. However, the study of the stacking configuration is useful for understanding how stacking alignments, intentional or not, affect the probability of having high G_I interfaces between fabric layers. Such alignment includes a combination of translation, rotation and turn over as shown in Figure 1.

In this work, the effect that the fabric alignment has on the fracture of PMCs was investigated experimentally through double cantilever beam (DCB) experiments. The objective was to understand how the contact interface between plain weave layers affects G_I of PMCs. Following the results, an analytical analysis was performed to investigate the effect that different stacking configurations have on the distribution of high G_I contact interfaces in PMCs. The analysis was performed with plain, twill 2×1, crowfoot and satin weaves for all possible orthogonal stacking configurations obtained through translation, rotation and turn over. The results enabled the suggestion of optimal stacking configurations for minimizing risks of low G_I interfaces in PMCs.

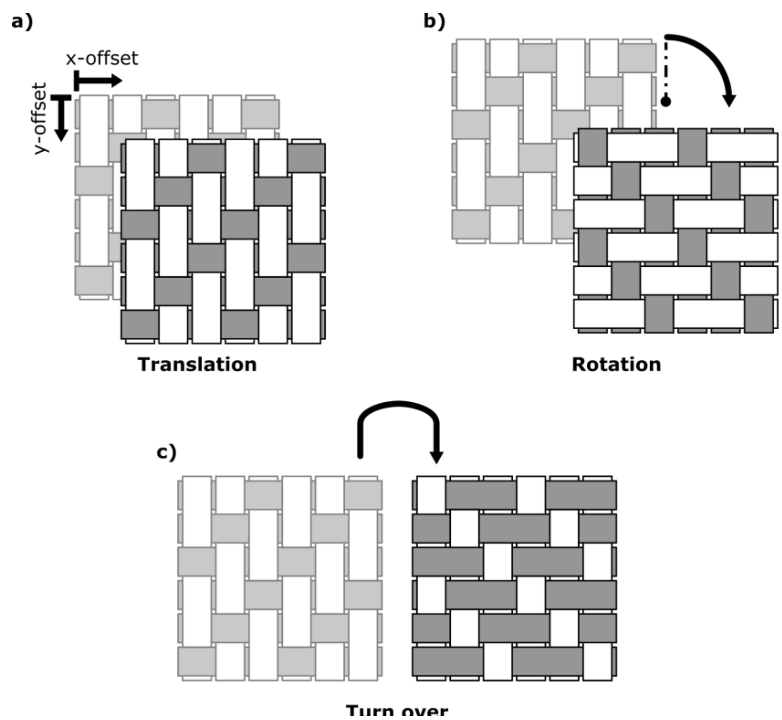

Figure 1. Types of fabric alignments, a) translation, b) rotation and c) turn over

2 METHODOLOGY

2.1 Specimens

The DCB specimens were made from carbon fibre/epoxy prepreg (CYCOM 5276-1/G40-800, Cytec) featuring a stacking sequence of $[0F/ 0_{10}/0F]_S$. The fabric layers were plain weaves with 10 mm wide yarns that were produced in-house using the same prepreg material as the unidirectional layers. Three different alignments of the plain weaves were tested (Figure 2). Alignment A consisted of contacting yarns having the same fibre orientation, alignment B featured contacting yarns with orthogonal fibre orientation, and alignment C featured maximum nesting. In addition, a 10 µm thick polytetrafluoroethylene (PTFE) film was inserted mid-stack for creating a 63.5 mm long edge delamination.

The specimens were cured in an autoclave between two aluminum patens. Specimens were pressed at 5.8 atmospheres and heated at a rate of 2.8°C/min to a temperature of 177°C that was held for 2 hours. Following cure, specimens were machined to their designed width, and hinges were bonded onto the DCB specimens using structural adhesive (Hysol EA 9396, Henkel). The lateral surfaces of specimens were painted white to provide better contrast between the delaminated and pristine areas of the DCB specimens.

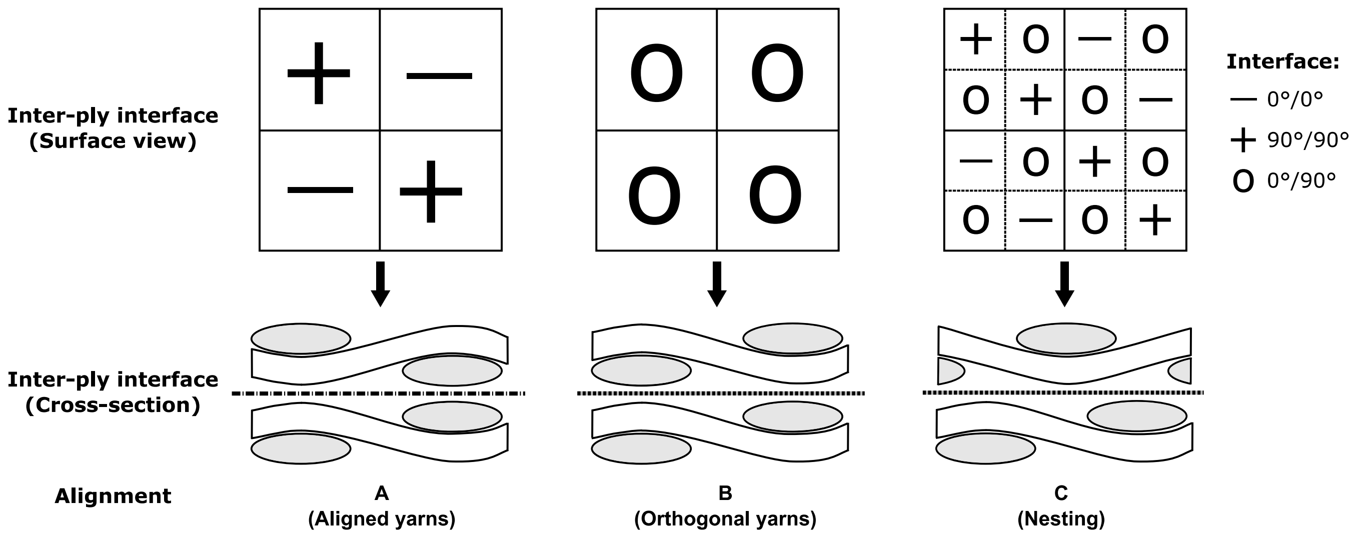

Figure 2. Unit cells for the fabric alignments

2.2 Mechanical testing

DCB testing was performed following ASTM standard D5528 for Mode I interlaminar fracture toughness of polymer matrix composites [12]. The specimens were mounted in a load frame (Insight, MTS) and pulled through their hinges at a rate of 5 mm/min until delamination growth exceeded 100 mm. Loads were recorded using a 1 kN cell and displacements were obtained from the crosshead motion.

Average propagation G_I values were defined as the energy per surface area that was dissipated during the creation of a new delaminated surface. The energy dissipated $U_{Dissipated}$ was calculated from the area under the load versus displacement curve minus the remaining elastic energy in the beams after delamination.

2.3 Analytical contact analysis

Mechanical testing is effective for measuring the effect that the stacking configuration has on G_I of PMCs. However, only a limited number of stacking configurations can be investigated and characterized experimentally. An analytical analysis was thus performed to investigate the effect that stacking has on Mode I fracture toughness between fabric layers. The analysis was only performed for orthogonal lay-ups and assumed an absence of resin rich regions between yarns.

The work investigated 5 weaves: a balanced construction (plain weave) and 4 unbalanced constructions featuring increasing levels of interlacing imbalance (Figure 3). The unbalanced constructions featured a balanced distribution of warp and weft yarns but different float lengths.

For the analysis, weaves were subjected to different alignment operations, including translation, rotation and turn over (Figure 1). This resulted in the investigation of 4 stacking configurations (Table 1) that were analyzed along the warp and weft directions. The procedure used for analysis consisted of:

1) Selecting a stacking configuration and weave construction.
2) Calculating the fraction area of high G_I interfaces, i.e. 0°/90° and 90°/90° interfaces, between fabric layers for every translation positions. The calculations were made with incremental offsets of 10% of the fabric unit cell.
3) Performing a statistical analysis to identify the average percentage of high G_I interfaces between fabric layers in the case where no effort was put towards aligning fabric layers, i.e. for a random alignment of fabric layers.
4) Repeating the procedure for all other stacking configurations and weave constructions.

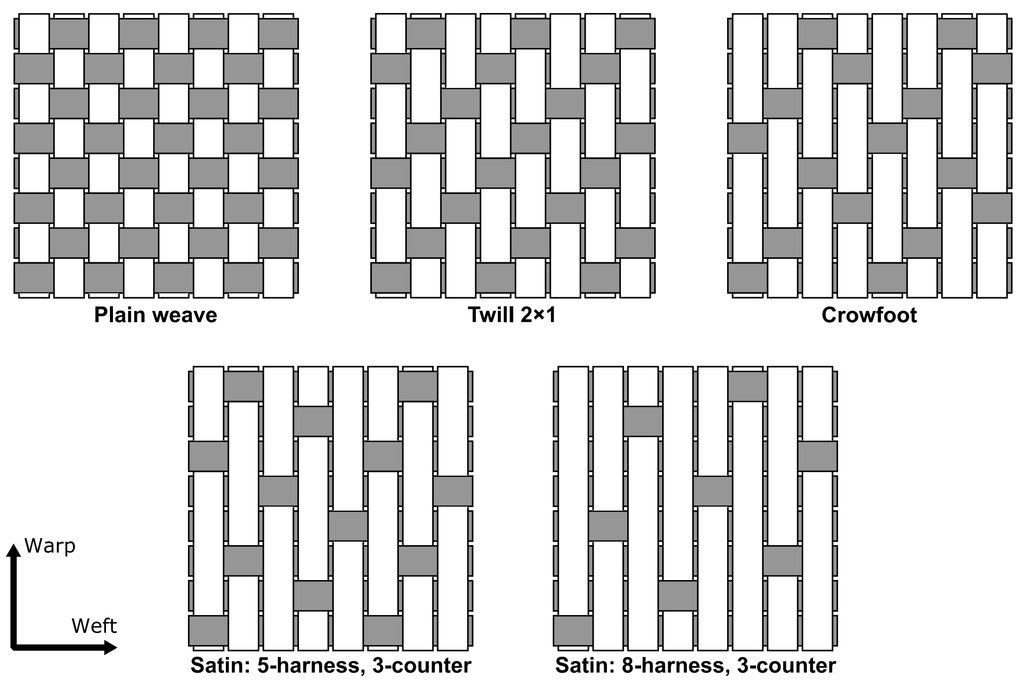

Figure 3. Weave constructions investigated for the analysis of the contact interface between adjacent layers

Table 1. Description of the stacking configurations

Stacking configuration	Fabric alignment	
	Bottom layer	Top layer
SA	None	Translation
SR	None	Translation and rotation 90°
FA	None	Translation and turn over
FR	None	Translation, rotation 90° and turn over

3 RESULTS

3.1 Mechanical testing

Experiments showed that delamination followed the topography of weaves. In zones of 0°/0° yarn contact, delamination propagated between fabric layers. Conversely, in zones of 90°/90° or 0°/90° yarn contact, some fibre bridging was observed. However, bridging was limited because fibres were constrained by yarn interlacing. This prevented complete fibre pull-out but resulted in some fibre breakage. Bifurcation of the delamination front was also observed at 90° yarns (Figure 4). This resulted in delamination fronts propagating above and below 90° yarns, leading to yarn debonding and yarn bridging.

Figure 4. Fractured surface of a woven specimen showing debonding of 90° yarns as indicated by shadows at crossovers

Clear differences in fracture surfaces were observed between the different weave alignments. Alignment A led to checkered surfaces with markings of 0° and 90° fibres (Figure 5a). Alignment B led to checkered surfaces with most markings showing 90° fibres (Figure 5b). Thus, delamination crossed the interfacial layer between adjacent weaves so that fracture was always against 90° fibres. Alignment C led to two types of markings at the fractured surface. In one case the delamination propagated against 90° yarns leading to a diagonal pattern (Figure 5c) while in the other case, the delamination propagated along the surface of a weave leading to a checkered pattern similar to alignment A.

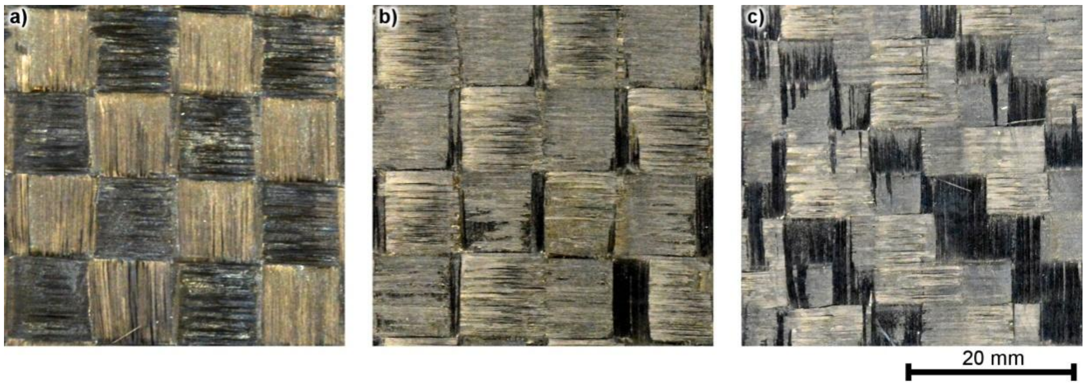

Figure 5. Fractured surfaces of woven specimens featuring fabric a) alignment A, b) alignment B, and c) alignment C

The average propagation G_I values were affected by the different fracture behaviours of the specimens. Results showed that G_I increases with the amount of yarn bridging, and such increase is linear with the percentage of 90°/90° and 0°/90° yarn interfaces (Figure 6) as opposed to 0°/0°. This resulted in fabric alignment A being the weakest, with 50% of 0°/0°, while fabric alignment B with no 0°/0° interface being the strongest. A linear model was used for describing G_I in terms of the fraction area A_f of the fabric contact interfaces covered by 90°/90° and 0°/90°:

$$G_I = 200A_f + 834 \quad \left[\mathrm{J/m^2}\right] \tag{1}$$

From this, it follows that fabric layers should be stacked in a specific orientation to maximise chances of obtaining alignment B. The effect of the stacking configuration was investigated by the analytical contact analysis that is presented below.

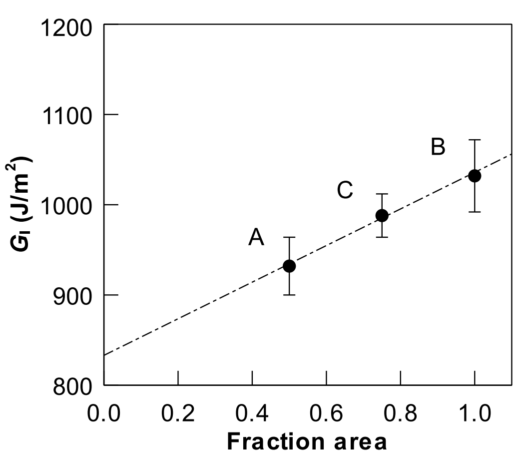

Figure 6. Average propagation G_I values for fabric alignments A (or aligned yarns), B (or orthogonal yarns) and C (nested yarns) based on the fraction area of the combined 90°/90° and 0°/90° yarn interfaces

3.2 Analytical contact analysis

The analytical contact analysis showed that the alignment between fabric layers has a significant effect on the percentage of high G_I interfaces (90°/90° and 0°/90° yarn contacts) in PMCs. This can be seen in Figure 7 which depicts the effect that translation has on the contact interface in PMCs when using stacking configuration SA, i.e. no rotation or turn over. In case SA, perfect alignment of any type of weave results in no 0°/0° yarn contacts that reduce G_I of PMCs, but any misalignment weakens that interface between fabric layers. From Figure 7, it is clear that the stacking of plain weaves features the most variation of contact interfaces and that increasing the level of interlacing imbalance of weaves lessens the effect of fabric misalignment. Based on the empirical model presented in Eqn. 1, the analytical contact analysis predicts that the plain weave tested in experiments leads on average to a G_I of 940 J/m^2 ± 17 J/m^2 when no effort is put towards aligning fabric layers.

The average fraction area of high G_I interfaces for a random alignment of fabric layers calculated for all stacking configurations appears in Figure 8. Results show that for stacking configuration SA, when fabric layers are not rotated or turned over, the distribution of high G_I interfaces is not affected by the warp or weft crack propagation direction, and that the percentage of high G_I interfaces increases with the level of interlacing imbalance. It follows that for stacking configuration SA, satin weaves provide the best solution for reducing weak interfaces.

The effect of stacking is highly similar for stacking configurations SR, FA and FR, but differs significantly from that of stacking configuration SA. Results show that alignment operations of rotation and turn over affect considerably the percentage of high G_I interfaces (Figure 8). In the weft direction the fraction area of high G_I interfaces increases with the level of interlacing imbalance. Conversely, in the warp direction the increase in interlacing imbalance increases the amount of low G_I interfaces markedly. Hence, these stacking configurations can lead to significant anisotropy at the interfaces between fabric layers. Only balanced weave constructions are not affected by the alignment operations of rotation and turn over.

Based on the results, it follows that special attention should be given to ensure that fabric layers are always laid along the same direction. This minimizes anisotropy at the interface and reduces the coverage of weak fibre interfaces. However, for highly unbalanced constructions such as satin weaves, designers may be tempted to add a plane of symmetry in the lay-up for obtaining parallel fibres on the top and bottom surfaces of the PMC. This leads to stacking configuration FA at mid-stack, resulting in a low G_I value along the warp direction. Currently, additional work is required for assessing whether the lower G_I value resulting from the stacking configuration FA outweighs the effect of an unsymmetrical lay-up. Alternatively, if the use of a symmetrical lay-up is imperative, a plain weave layer could be interleaved between unbalanced weaves at mid-stack for reducing the number of 0°/0° yarn interfaces.

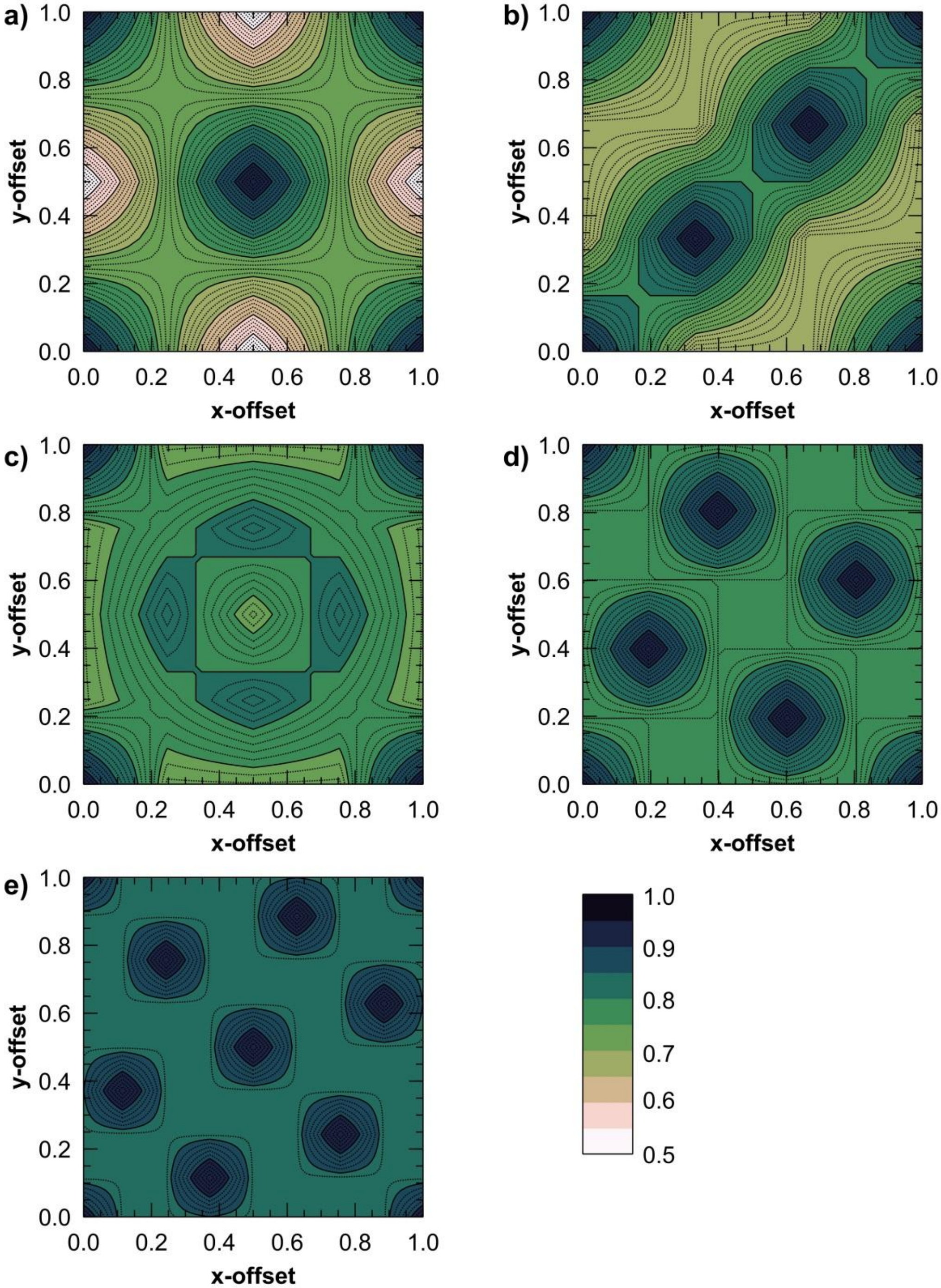

Figure 7. Effect of fabric translation on the fraction area of 90°/90° and 0°/90° yarn interfaces using stacking configuration SA along the warp direction for a unit cell featuring a) plain, b) twill 2×1, c) crowfoot, d) satin 5-harness 3-counter and e) satin 8-harness 3-counter weaves

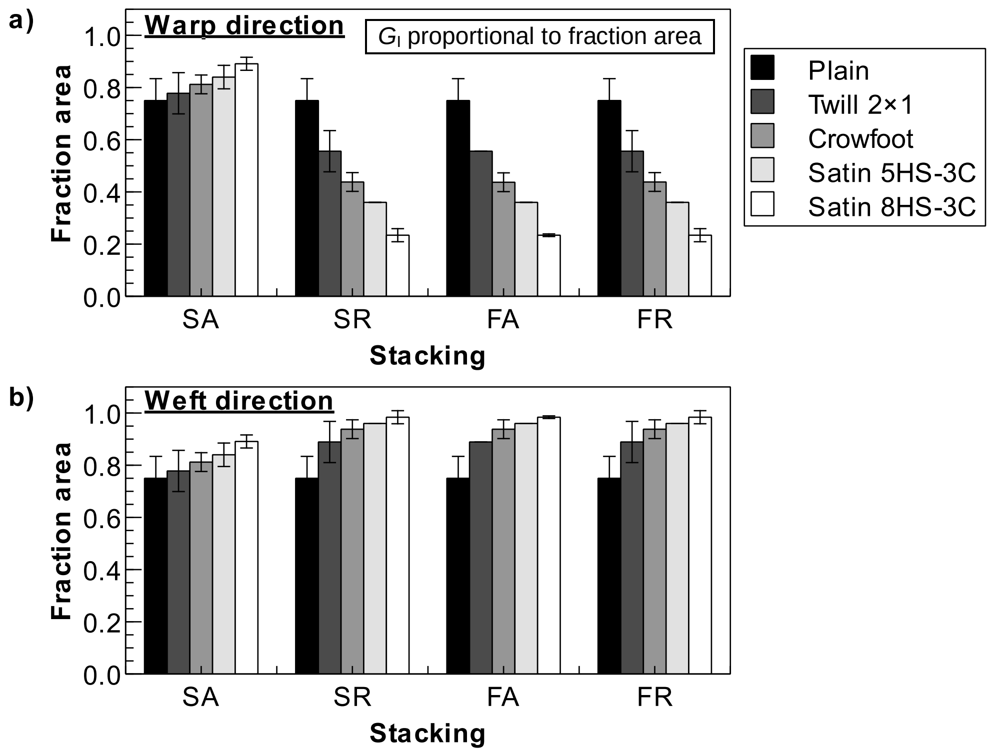

Figure 8. Fraction area of 90°/90° and 0°/90° yarn interfaces for a random alignment of fabric layers with different weaves and stacking configurations along the a) warp and b) weft directions

4 CONCLUSIONS

Results showed that the stacking configuration of fabric layers has a strong influence on the G_I of PMCs. Key findings are:

- G_I can vary by more than 10% due to the alignment of plain weave layers.
- G_I decreases with increasing levels of 0°/0° yarn contact interfaces.
- The percentage of 0°/0° yarn contact interfaces in a lay-up depends on weave construction and stacking configuration.
- The effect of the stacking configuration increases with increasing levels of interlacing imbalance.
- Highly unbalanced weaves, such as satin weaves, can provide the lowest amounts of 0°/0° yarn interfaces, but only when layers are aligned in a specific direction.
- Plain weaves are the least affected by the stacking configuration and alignment of fabric layers.

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