IOP Conference Series: Materials Science and Engineering

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To cite this article: D Raja *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **912** 022041

IOP Conf. Series: Materials Science and Engineering **912** (2020) 022041 doi:10.1088/1757-899X/912/2/022041

Analysis of carbon fibre bone plate for "B1" type periprosthetic femoral fracture

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Abstract. Peri-prosthetic Fractures after Total Hip Arthroplasty (THA) are a dreaded complication which happen frequently due to aging and day to day normal activities of the patient. These fractures happen below the cemented/ uncemented stem, either straight/oblique direction concerning the transverse plane. Treatment requires surgical stabilization using metal plates, screws, cables and/or clamps. However, stress shielding in bone due to metal plates can be reduced by designing implants with fibre reinforced polymer composites. The present study aims to study the stress distribution in a composite plate using carbon fibre for a B1 type periprosthetic femoral fracture fixation in immediate postoperative (IPO) condition and compared with metal plate by varying geometrical parameters, laminate stacking sequence and fibre orientation. To evaluate the axial stiffness and surface stress of composite plate fixation finite element (FE) analysis was done. Various parameters like axial movement, shear movement, strain and maximum stress are considered to measure the fracture stability and the healing process through FE method. The results showed that the proposed composite bone plate could be a potential candidate for replacement of metallic bone plates for periprosthetic fracture in the femur.

1. Introduction

Periprosthetic femoral fractures (PFF) in patients who have undergone Total Joint Arthroplasty (TJA) in hip or knee, are complications commonly seen in the elderly and frail subjects with associated osteoporosis [1]. These fractures present unique challenges for the operating surgeon and surgical management is fraught with dangers. The incidence of Postoperative PFF after primary replacement surgery of hip and knee joint ranges between 4.5% to 18%. Over the past 3 decades, with rising numbers of TJAs, the number of revision surgeries are also growing rapidly. PFFs are classified according to their fracture pattern and the surgical management varies accordingly, using plate-screw constructs along with cables, wires as well as bone grafting augments. The long term results after surgical treatment are sub optimal, probably due to poor bone quality, osteolysis and especially due to stress shielding because of the plate-screw construct [2].

In the past three decades, several studies have been conducted to study the effects of stress shielding. Lever et al. (2010), studied the biomechanical behaviour of three different screw plate and cable plate using twelve cadaver femurs for axial, torsional, and four-point bending tests to obtain stiffness value and suggested that screw plate system showed the maximal stability [3]. Choi et al. (2010), studied the differences in stiffness between three constructs for the fixation of Vancouver B1 periprosthetic femoral fractures, and showed the lateral locked plate with anterior locked plate was significantly stiffer than some other fixations [4]. Lenz et al. (2012), compared the LCP and A-LCP plates for Vancouver B1 fracture using twelve fresh frozen, human femora and concluded that the bicortical locking screw placement adjacent to the prosthesis stem enhance the mechanical stability and strength in proximal plate fixation [5]. Moazen et al. (2013) studied the effect of fracture stability of a locking plate fixation the performance of stainless steel versus titanium plate fixations the results showed the single locking plate fixation provides the callus formation without risk of plate fracture [6]. Wang et al. (2016) conducted the simulation in three internal fixation and suggested that the Multi-directional locking plate system is more stable and stronger than the other locking plates [7]. Leonidou et al. (2015) investigated the effect on locking plate fixation and stated that the alternate method is required for poor bone quality and for poor bone quality and irregular fracture angle [8]. Most of the previous studies were used metal plates, due to high stiffness in all direction the fixation was failed (stress shielding) shown continuous drawback. Bagheri et al (2014) developed a hybrid composite plate and evaluated the effects and strength of the composite structure in normal loading condition [9]. Similarly, studies were conducted to study the inner structure behaviour of pre- and post-surgery condition. Kim et al. (2011) studied the biomechanical performance in shaft fracture considering strain and time dependent properties for callus and suggested that composite bone plate provides the sufficient strain distribution in the fracture site [10]. As per Samiezadeh et al. 2015, composite plates could increase the compressive force at the fracture site compared to metal plate [11] without much compromise in the stiffness in the lateral direction. Composite plate considering the geometrical parameters to fulfil the requirement of axial movement in the fracture site to increase the compression force.

Thus, the primary objective of the present work is to study the effect of lamination configuration for carbon fibre (CF)/epoxy structure in a composite bone plate for achieving selective stress shielding, i.e. higher axial movement with low shear movement. In this study the strength of the plate, maximum stress distribution, axial and shear movement near to the fracture fragment region of the bone plate having different lamination configuration, width and thickness are computed using finite element (FE) method and compared with conventional metal plate.

2. Materials and Methods

A three-dimensional FE model of right femur was developed in the present work. The outer surface of the model was extracted from dry femur bone using Portable Coordinate measuring machine with laser scanner. This surface model was refined using Geomagic Design X. The model was further improved with modification using Solidworks software for amending errors in the IGES (Initial Graphics Exchange Specification) file format. The thickness of the cortical wall and cancellous region was created as per literature [12]. Femur head was cut at an angle of 55º from greater trochanter to lesser trochanter region to fit a cemented hip implant. Fracture gap of 4mm were created in transverse direction below the tip of the cement potting cube [13]. Three-dimensional plates with 12 holes were modelled as solid and surface for length of 194mm with two different thicknesses, 5.6mm and 6mm, and two different widths, 16mm and 18mm as per manufacturer's specifications. Unilateral and bilateral screws of 4.5mm diameter were modelled as solid bodies and positioned at transverse fracture along with plate. The model creation of stem, plate and screw was based on information given in the manufacturer's catalogue (Zimmer, Indiana, USA).

Three-dimensional solid and surface models are meshed with 4 node tetrahedral elements and 4 noded shell elements in Ansys 19.0. Contacts were defined between all interfaces using contact element. Plate and bone were considered as "No separation condition" and all the other interfaces were set as "Bonded condition" [9, 14]. All material properties of metal plate (C15) and laminate stacking sequence and fibre orientation for composite plate (C1-C14) were assigned based on published literature [11, 15], material properties and configuration used in the FE models was shown in table 1 and 2.

IOP Conf. Series: Materials Science and Engineering **912** (2020) 022041 doi:10.1088/1757-899X/912/2/022041

Table 1. Material properties used in the metal and composite plate fixation FE models.

Property	E_X (GPa)	E_Y (GPa)	G_{XY} (GPa)	ν_{xy}	ν_{yz}
Cortical bone	16.7	-	-	-	-
Cancellous Bone	0.1	-	-	-	-
Bone cement	2.45	-	-	-	-
Hip Implant (CoCrMo)	210	-	-	-	-
Screws (316L Stainless steel)	193	-	-	-	-
Metal bone plate (Ti–6AL–4V)	113.8	-	-	-	-
CF/epoxy (Composite prepregs)	121	8.6	4.7	0.27	0.4

Table 2. Laminate stacking sequence and fibre orientation for composite plate (C1-C14) and metal plate (C15).

Configuration	Stacking sequence
C1	$[0_C/0_{8F}]_S$
C2	$[\mp45_2/45/0/-45/0/45/0/-45/90_3]_S$
C3	$[\mp45/0/\pm45_2/\mp45/0_2/90_3]_S$
C4	$[\mp45/0/\mp45/45/0/\mp45/-45/0/90_3]_S$
C5	$[\mp45/0/\pm45/0/\pm45/0/\mp45/90_3]_S$
C6	$[\mp45/0_2/\pm45_2/0/\mp45/90_3]_S$
C7	$[\mp45/0_2/45/0/-45_2/45_2/-45/90_3]_S$
C8	$[\mp45/0_2/45/0/-45_2/45/0/90_4]_S$
C9	$[\mp45/0_2/45/0_2/-45_2/45/90_4]_S$
C10	$[\mp45/0_4/\pm45_2/90_4]_S$
C11	$[\mp45/0_4/45/0/-45_2/45/90_3]_S$
C12	$[\mp45/0_4/45/0/-45/0_2/90_3]_S$
C13	$[\mp45/0_6/\pm45/0/90_3]_S$
C14	$[\mp45/0_8/90_4]_S$
C15	Ti-6AL-4V

Fracture with fixation of IPO condition were considered for simulation. The distal region was rigidly fixed, and the stem was loaded under axial load of 2300N to test the performance of PFF fixations [16]. A mesh convergence study was undertaken to find the minimum number of elements. Five tetrahedral meshes from 40000 to 200000 elements were created and applied with the uniformly distributed compression load of 500 N on the top of the stem, while the inferior end was constrained in all degrees of freedom. The displacement of the meshes ranged from 0.173 to 0.203 mm. There was 5% difference in the displacement except for the first two meshes. So, mesh with 120000 elements (mesh size 2 mm) was used for further analysis. The meshed model of femur with implant is shown in figure 1.

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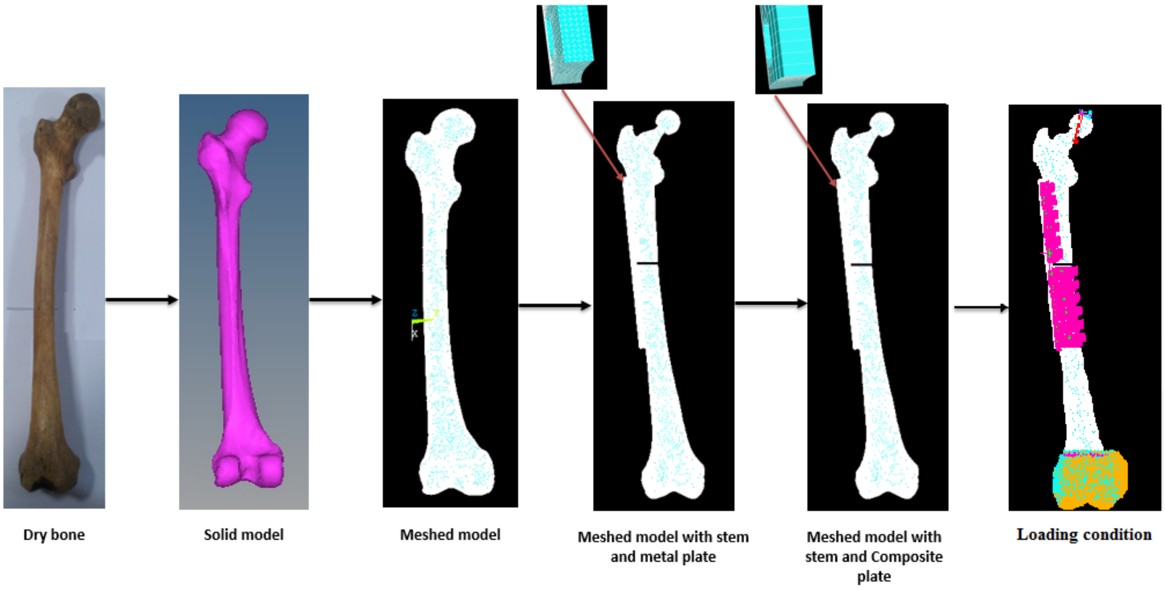

Figure 1. Stages of development of the finite element model of femur with implants and the loading condition.

3. Result and Discussion

A three-dimensional FE model of femur was developed with implant and studied the stress distribution, axial / shear movement and shear stress in the metal and composite bone plate. Initially, the femur bone with metal plate (C15) were analysed and compared the axial displacement with literature [6] for validation. The axial displacement was found slightly higher than the previous study may be due different in geometric structure and mesh size. Further, the composite plate (C1-C14) were modelled with different geometry structure and different laminate stacking sequence and fibre orientation. This FE study analysed all the 15 models under maximum compression load [16] to select the best suited configuration for composite plate. The stress distribution of metal and composite plate in compressive load is shown in figure 2.

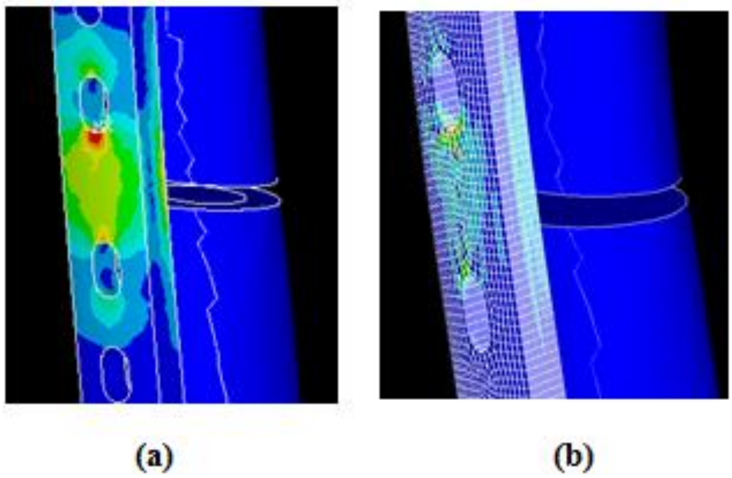

Figure 2. Stress distribution in (a) metal plate and (b) carbon fibre plate.

Maximum stresses generated in different bone plate, as described in Table 2, are shown in figure 3. It can be noted here that the stresses generated in the composite plates depend significantly on the fibre orientations in the lamina but are generally higher than that of the metal plate. Stresses at the composite bone plate are significantly low for the fibre orientation types C1 and C2. Especially, composite plate of 18mm width and 6mm thick (for C1 and C2) results showed decreases of stresses at the fracture site. Figure 4 shows that the axial movements are higher for the composite plates. Composite with C2 configuration showed 28% higher movement comparing with metal plate, and movement are within the limit. Due to increase in axial movement, compression force in the fracture site is increased, stress shielding is reduced and thus the bone remodelling is improved.

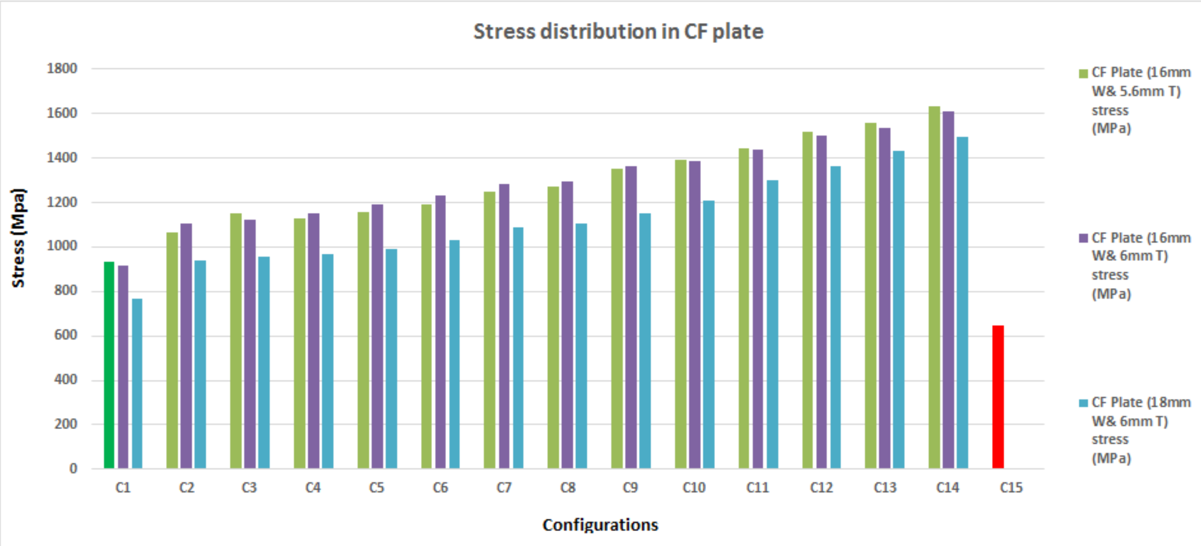

Figure 3. Maximum stress in composite plates with different configurations and metal plate.

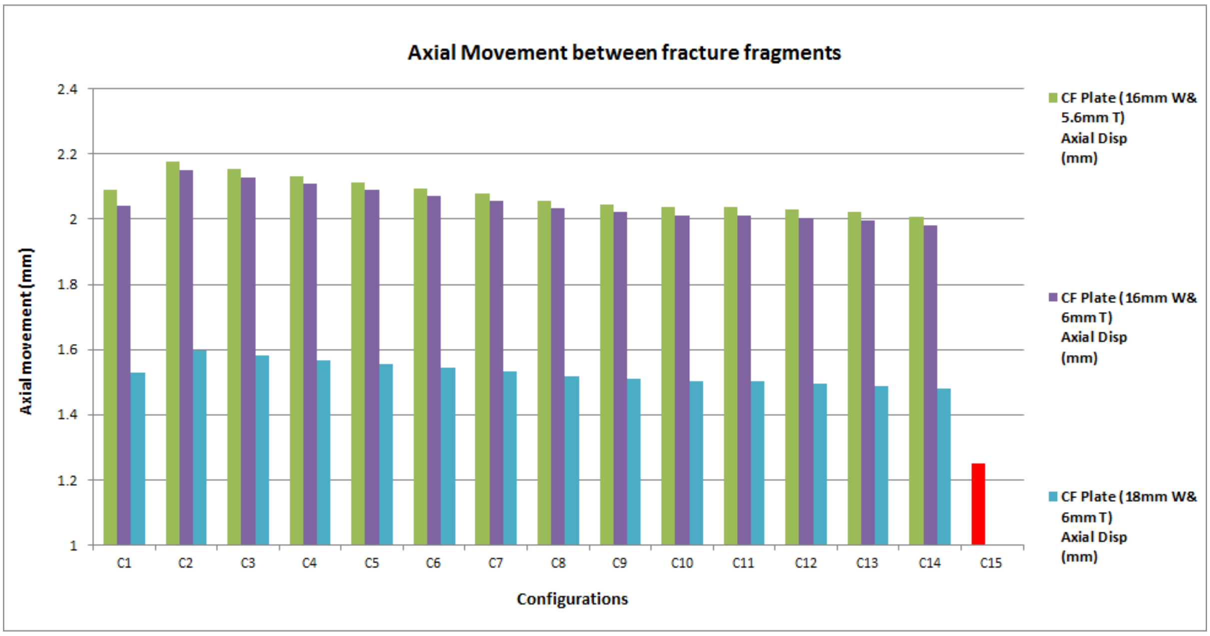

Figure 4. Axial movement in carbon fibre plate for different configurations Vs Metal plate.

Shear movement and shear stress of the composite plates and the metal plate are shown in figures 5 and 6. Shear movement is one of the major factors while designing the bone plate, lesser shear movement will increase the stability of the bone plate fixation. The stress in the fractured region needs to be shielded selectively in this direction. Shear movement was quite high in all configurations of composite plate while comparing with metal plate. However, shear stresses in the composite bone plate of C1 and C2 configuration was decreased at the fracture site. C2 configuration showed 42% lower shear stress in comparison with metal plate.

Hence, the above analyses that C2 type composite bone plate have better response compared to other plates for most of the aspects considered in this study. But there are still scope for improvements in the direction of decreasing the shear movement. It could be noted here that, in the present study 14 different configurations are chosen to get some idea of the role of the fibre directions in each lamina, the roles of width and thickness of the plate for achieving the desired property. The results showed that composite bone plates have the potential to achieve the targeted properties and can successfully replace the bone plates as a better alternative. There might exist other configurations of the composite bone plate for which further improvement could be achieved. In this work the fibre and matrix properties are not varied. Variations in those materials may even improve the properties further.

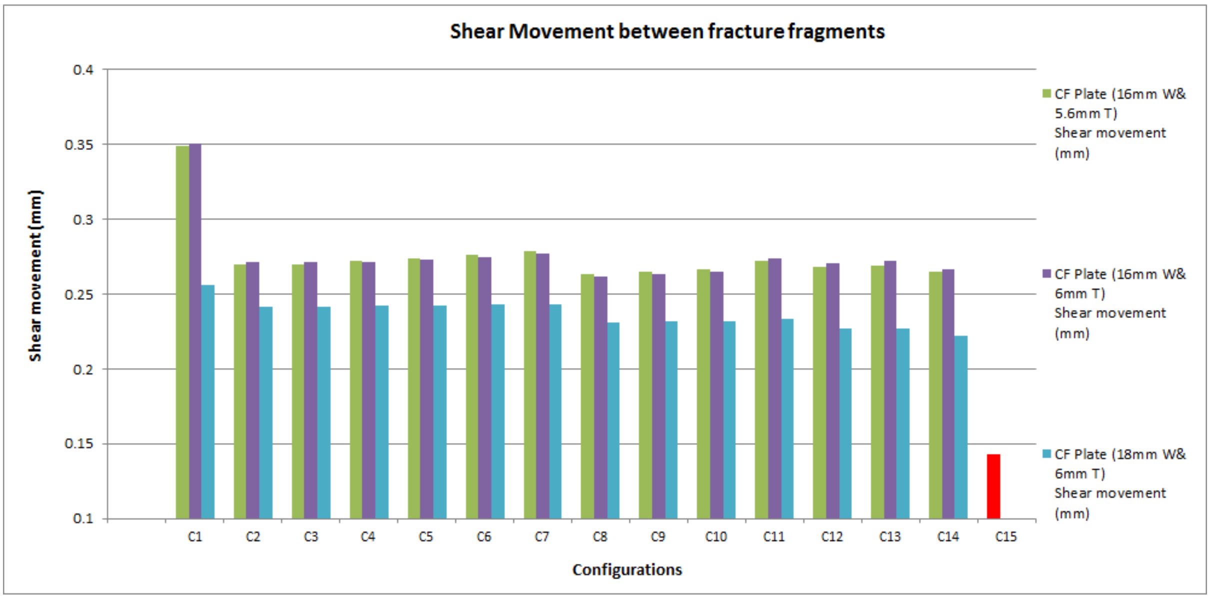

Figure 5. Shear movement in carbon fibre plate for different configurations Vs Metal plate.

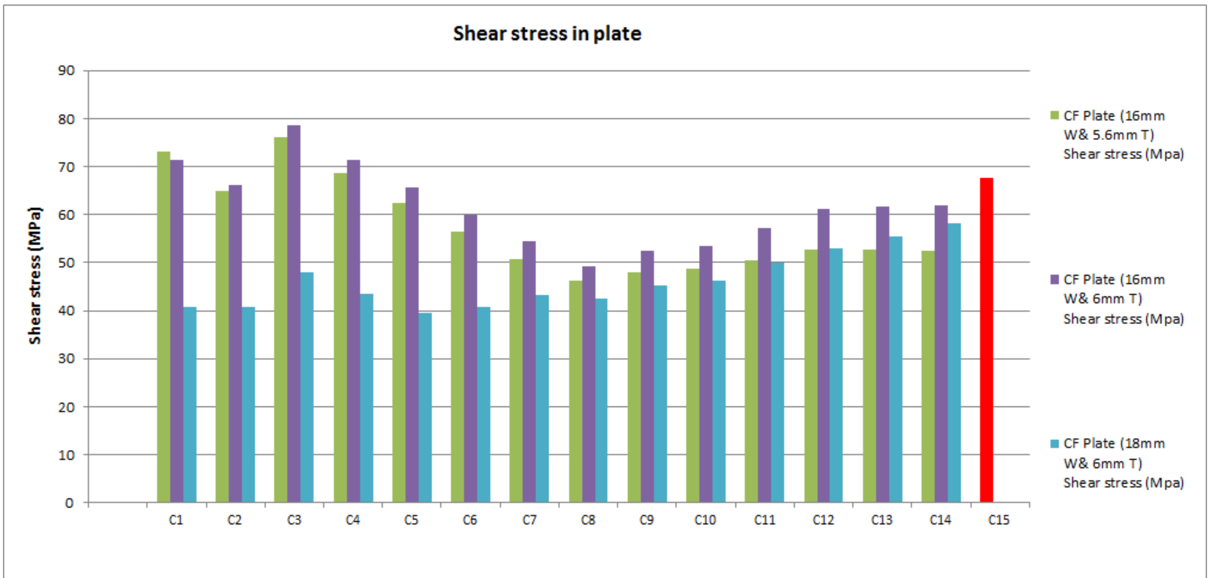

Figure 6. Shear stress distribution in carbon fibre plate for different configurations Vs Metal plate.

4. Conclusion

Three dimensional finite element model of traditional metal plate and composite plates with 14 different configuration was developed and analysis were performed. From the analysis results, it has been observed that metal fixation plate can be replaced by composite plate. Stress distribution is uniform for the C1 and C2 type of composite plate fixation. Shear stress is quite low compared to metal plate especially for C2 type of composite plate. Relative displacement along the axial direction of the composite plate is quite better for the osseointegration in case of bone remodelling. The results of this study also suggest that further study in this direction may find solutions with further improvement in the targeted properties.

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