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Research Paper

On optimization of a composite bone plate using the selective stress shielding approach

Saeid Samiezadeh[a], *Pouria Tavakkoli Avval*[a], *Zouheir Fawaz*[b], *Habiba Bougherara*[a,*]

[a]*Department of Mechanical and Industrial Engineering, Ryerson University, Toronto, ON, Canada*
[b]*Department of Aerospace Engineering, Ryerson University, Toronto, ON, Canada*

A R T I C L E I N F O

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A B S T R A C T

Bone fracture plates are used to stabilize fractures while allowing for adequate compressive force on the fracture ends. Yet the high stiffness of conventional bone plates significantly reduces compression at the fracture site, and can lead to subsequent bone loss upon healing. Fibre-reinforced composite bone plates have been introduced to address this drawback. However, no studies have optimized their configurations to fulfill the requirements of proper healing. In the present study, classical laminate theory and the finite element method were employed for optimization of a composite bone plate. A hybrid composite made of carbon fibre/epoxy with a flax/epoxy core, which was introduced previously, was optimized by varying the laminate stacking sequence and the contribution of each material, in order to minimize the axial stiffness and maximize the torsional stiffness for a given range of bending stiffness. The initial 14×4^{14} possible configurations were reduced to 13 after applying various design criteria. A comprehensive finite element model, validated against a previous experimental study, was used to evaluate the mechanical performance of each composite configuration in terms of its fracture stability, load sharing, and strength in transverse and oblique Vancouver B1 fracture configurations at immediately post-operative, post-operative, and healed bone stages. It was found that a *carbon fibre/epoxy* plate with an axial stiffness of 4.6 MN, and bending and torsional stiffness of 13 and 14 $\text{N}\cdot\text{m}^2$, respectively, showed an overall superiority compared with other laminate configurations. It increased the compressive force at the fracture site up to 14% when compared to a conventional metallic plate, and maintained fracture stability by ensuring the fracture fragments' relative motions were comparable to those found during metallic plate fixation. The healed stage results revealed that implantation of the titanium plate caused a 40.3% reduction in bone stiffness, while the composite plate lowered the stiffness by 32.9% as compared to the intact femur. This study proposed a number of guidelines for the design of composite bone plates. The findings suggest that a composite

*Correspondence to: Department of Mechanical and Industrial Engineering, Ryerson University, 350 Victoria Street, Toronto, ON, Canada M5B 2K3. Tel.: +1 416 979 5000x7092; fax: +1 416 979 5265.
E-mail address: habiba.bougherara@ryerson.ca (H. Bougherara).

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bone plate could be customized to allow for moderate compressive force on the fracture ends, while remaining relatively rigid in bending and torsion and strong enough to withstand external loads when a fracture gap is present. The results indicate that the proposed composite bone plate could be a potential candidate for bone fracture plate applications.

1. Introduction

Bone plates could be used to fix almost any diaphyseal fracture in long bones. However, with the favourable results of intramedullary (IM) nails, the indication for plates has been limited to those cases where IM nailing is impractical or difficult (Rockwood et al., 2010). For instance, in patients with extremely narrow medullary canals or those with existing hardware, plates remain an excellent option (Koval and Zuckerman, 2006; Rockwood et al., 2010). The ultimate goal of plate fixation is to stabilize the fracture by driving fracture ends together, allowing for both primary and secondary bone healing (Aro and Chao, 1993; Rockwood et al., 2010).

Despite recent advancements in implant design and surgical techniques aiming to protect bone vascularity and to facilitate healing, complications are still prevalent, and include malunion, nonunion, hardware failure, and bone refracture (Browner, 2009; Koval and Zuckerman, 2006; Olmstead, 1991). Plates are designed to apply compressive force at fracture ends. However, in the presence of a gap at the fracture site opposite to the location of the plate, they can be subjected to excessive bending moments as the fracture site acts as a fulcrum around which the plate bends (Müller et al., 1991). This situation can occur during ambulation, making the plate vulnerable to bending failure. As the fracture gap increases, so too does the stress in the plate (Askew et al., 1975), necessitating that it be stiff and strong enough in bending. Metallic plates, composed mainly of stainless steel or titanium (Ti) alloys, can provide appropriate stability at the fracture site and are widely used as fracture fixation devices where applicable. However, their high axial rigidity causes the plate to bear the majority of the load once implanted, shielding the bone from the load to which it would be naturally subjected (Bagheri et al., 2013; Ganesh et al., 2005). This situation can lead to a reduction in the compressive loads at the fracture site, which would be detrimental to healing as callus formation decreases with reduced compressive force (Bartel et al., 2006). Additionally, even after union, the reduction of mechanical stresses on the femur leads to bone resorption at the vicinity of the implant over time, which is referred to as “stress shielding” (Wolff et al., 1986). This condition makes the bone prone to refracture, which is considered a difficult-to-manage complication of plating (Tonino et al., 1976). Several studies reported enhanced healing with the use of more flexible bone plates (Ali et al., 1990; Foux et al., 1997; Tonino et al., 1976; Woo et al., 1974). However, excessive flexibility results in poor fixation and subsequent complications, such as malunion or non-union (Epari et al., 2007; Kenwright and Goodship, 1989; Tayton and Bradley, 1983; Terjesen and Apalset, 1988). Therefore, controversies remain regarding the optimal fixation rigidity (Browner, 2009; Epari et al., 2007).

Reducing the stiffness of the fixation plate could favourably increase the load levels at the fracture site and stimulate remodelling of the callus, but it may also compromise the stability of the fracture by increasing unfavourable (e.g. shear and torsional) interfragmentary movements, which are detrimental to fracture healing (Augat et al., 2003). Furthermore, stress shielding is not always disadvantageous, and can actually be beneficial in fracture healing, as if the implant adequately counters bending, torsional, and shear stresses while only fractionally resisting compressive stress, it can thereby stimulate remodelling of the callus at the fracture site (Woo et al., 1984). This concept is referred to as “selective stress shielding” (Poitout, 2004), and is gaining traction in the design of fixation implants as the new generation of materials become available.

In conventional Ti bone plates, axial stiffness could be lowered by reducing the thickness of the structure. However, bending and torsional stiffness will then drop proportionally to the 3rd power of the thickness. Another way of tailoring the stiffness of a metallic bone plate is to make it tubular, as has been done previously in the literature (Woo et al., 1984). However, this would increase the stress in the structure, making it prone to fatigue failure (Rockwood et al., 2010). In contrast, a composite material has the potential to be tailored and adapted based on specific requirements through changing the arrangement or volume fraction of the fibres (Cifuentes et al., 2012). Several in-vitro and in-vivo studies considered composite materials as an alternative material of choice for bone plate applications aiming to reduce the adverse effects of stress shielding induced by a rigid implant (Ali et al., 1990; Fujihara et al., 2004, Woo et al., 1974). Early studies reported less plate-induced osteopenia and superior biocompatibility with the use of carbon fibre (CF)/epoxy bone plates (Ali et al., 1990, Bradley et al., 1980; Tayton et al., 1982). Fujihara et al. (2003) proposed a braided carbon/PEEK composite structure for bone plate applications and investigated the effect of plate thickness on plate bending stiffness. Later, Huang and Fujihara, 2005 compared the bending stiffness of six composite bone plates (using unidirectional (UD) fibre prepregs, braided fabrics, and knitted fabrics), and concluded that a bone plate made of small angle braided fabrics can lead to the best mechanical performance. Several studies showed increased bone stress with the use of composite bone plates through computer simulations or in-vitro testing (Bagheri et al., 2014b; Ganesh et al., 2005; Siddiqui et al., 2014; Veerabagu et al., 2003). Kim et al. (2010) used the finite element method to examine