Optimum Design & FEA of Tibia Fractured Composite Bone Plate

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Purpose: to evaluate the optimum design of laminated glass-fiberPolyvinyl Chloride (PVC) -matrix composite bone plate based on genetic algorithm (GA). This plate used to fix tibial fractures.
Materials and method: Conventional structure of a bone plates made off stainless steel, titanium alloys and other metals used to treat tibial fractures have many drawbacks. This paper introduces an optimal design of a composite bone plate. The optimized design is then tested by finite element method. The number of layers, fiber orientations, fiber volume fractions and layer thickness are considered as the optimization variables. Simplified micro-mechanics equations are used to estimate the stiffness and strength of each layer using the optimization variables and material constituent's properties. The lamina stresses for thin composite slips subjected to force and/or moment resultants are determined using the classical lamination theory. The first-ply failure strength is computed using the Tsai–Wu failure criterion. A genetic algorithm is adapted to obtain the optimal design for plate model problem.
Results: The results of the optimization work showed that the optimized plate is composed of 5 layers showing the volume fraction, fiber orientation and thickness of each layer. The maximal von mises stress on the plate is also calculated using FEA.

Keywords*:*Bone plate, Composite material, Genetic algorithm, and Optimization, FEA.

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1. Introduction

Tibial fractures are one of the most frequent human fractures resulting from falls from heights or accidents. These fractures can be treated by two different methods regarding to fracture's type and its state. In the case of high-energy bone fractures that result from motor vehicle accidents, a high height fall or an industrial accident causing significant amounts of bone damages, an indirect bone healing method such as a casting is usually used. While, simple (low-energy) fractures of long bones, a direct bone healing method, fracture of this type are fixed by bone plates to provide immobilization at the fracture site and minimize the fracture gap, thus helping in bone healing and formation of endosteal callus [1].

The bone plate used to fix the fractured bone segments in position, allowing critical compressive stresses in order to accelerate bone healing. [2]

Locking compress plate (LCP), which is lightweight, comfortable and convenient for patients to ambulate [3], is very attractive to be used as external fixators in the treatment of distal tibial fracture, especially compared with conventional external fixators. LCP has been successfully used in open or closed distal tibial fractures and shown good rates of union and ankle-joint motion [3–6]

Conventional bone plates are made of metals such as stainless steel, Co–Cr alloys, or titanium alloys. These devices provide excellent reductions in the number of bone fragments used and have the necessary strength to fix and support the fracture [7-8]. Because conventional plates made of metals have Young's moduli are much higher than those of human bones, they induce stress-shielding effect that occasionally resulting in much higher load transfers to the bone plate than to the fractured bones. This occasionally causes osteoporosis and, at worst, can lead to bone necrosis in the fractured bones [9-12].

The influence of size and material of plate on bone fracture healing stabilized by far cortical locking technique is still unclear in clinical practice [13-18].Acceleration of bone healing is related to strain value of fixed bone plate and bone atrophy, or osteoporosis that may lead to bone re-fracture after plate removal. Moreover, metal alloys used in titanium plate release metal ions such as Nickel or Chromium (due to corrosion and wear) which may cause loosening of the implant, patient discomfort, or allergic skin reactions, infection and tissue damage [19-20]. Moreover, conventional plates are radiopaque (which make surrounding bone difficult to monitor using computerized tomography (CT) andmagnetic resonance imaging (MRI) scans). Another shortcoming of metal implants is their fatigue failure under cyclic loads [21-22]. To overcome the drawbacks of metal plates, flexible materials such as polymers and fibrous composites have been examined to design various bone plates [23-24].

Bone plates made of composite materials are possible solutions [25]. Fiber reinforced polymers have low stiffness and high strength, properties which make them suitable for different orthopedic applications. Fiber reinforced polymers materials have a wide range of mechanical properties (close to those of the bone tissue) that can be achieved by controlling the volume fraction (Vf) and local and global arrangement of the fibers [21].*Several studies used to solve the drawbacks of metal bone plate.Veerabagu et al. investigated the carbon–epoxy composite material for bone-plate application. They have determined that the longitudinal strain in bone and the bone plate are higher with composite plate than that with steel plate for a given loading [26].Ali et al. compared the mechanical properties of carbon fiber composite bone plates with conventional bone plate made of steel and titanium. They have found that composite plates have less stiffness with good fatigue properties [27]. Fujihar and Veerabaguet al. investigated the fabrication process of a carbon/PEEK composite bone plate and its mechanical performance by 4-point bending tests to verify the analytic results [28].*

Finite element analysis used in an orthopedic setting to determine the actual mechanical behavior and response induced in a bone by application of a fracture fixator. FE method is used in orthopedic research in different area such as, analysis and design of orthopedic devices, analysis of tissue development, remodeling and degeneration and skeleton analysis. FEA first applied in orthopedic field was in 1972. Thereafter, its applications in orthopedic field are developed with techniques and complexities increasing rapidly in recent times [29-30].

Mehboob, et al. studied the influence of design factors of a functionally graded biodegradable composite bone plate on the healing of a tibia fracture. A finite element model of a human fractured tibia was constructed, and the bone fragments were assembled with a bone plate and screws. The Taguchi method with the design of experiments (DOE) wasused for optimal design of the bone plate. To optimize the design parameters of the bone plate and maximize the healing performance, signal-to-noise ratio was used, as a larger signal-to-noise ratio was better [31]. Samiezadeh et al. used classical laminate theory and the finite element method to optimize 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. 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 $N.m^2$, 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 platefixation. They proposed a number of guidelines forthe design of composite bone plates [32].Park, et al. investigated the mechanical performance of a bone plate made of a glass/polypropylene composite material for the biologic fixation of diaphyseal long bone fractures [33].

Mehboob, et al. investigated the influence of design factors of a functionally graded biodegradable composite bone plate on the healing of a tibia fracture. A finite element analysis of a human fractured tibia was applied, and the bone fragments were assembled with a bone plate and screws. Four design parameters of a composite bone plate were studied to investigate their influence on bone fracture healing. The Taguchi method with the design of experiments (DOE) was used for optimal design of the bone plate. The optimum levels of design parameters of the bone plate were selected, and the optimal design of a bone plate was suggested to maximize the healing performance. The optimal condition of designparameters was successfully determined by using the Taguchi method, and it was shown to maximize the healing of bone fractures [34].

N.D. Chakladar, et al. investigated the feasibility of adopting advanced composite materials to overcome stress shielding effects by optimising the geometry and mechanical properties of the plate to match more closely to the bone. An ulnar transverse fracture is simulated and finite element techniques are applied to investigate the feasibility of a composite-plated fractured bone construct over a stainless steel equivalent. Numerical models of intact and fractured bones are analysed and the mechanical behavior is found to agree with experimental data. The mechanical properties are tailored to produce an optimized composite plate, offering a 25% reduction in length and a 70% reduction in mass. The optimized design may help to reduce stress shielding and increase bone healing rates [35].

A genetic algorithm searches an optimal solution for the problems by manipulating a population of strings (chromosomes) that represent different potential solutions, each corresponding to a sample point from the search space. For each generation, all the populations are evaluated based on their fitness. An individual with a larger fitness has a higher chance of evolving into the next generation. In the present case, an individual member of the population corresponds to a particular laminate design and its chromosome consists of the fiber orientations, fiber volume fractions, lamina thicknesses and layers number [36].

All of the previous researchers focused on stress analysis, mechanical testing of plate and finite element analysis of bone plate models else Mehboob, et al. and Samiezadeh et al., N.D. Chakladar, et al [31,32, 34, 35]. Optimization work in their papers [31, 32, 34, 35] used only one parameter (thicknes or length) to find the optimal design and build their theories. But, In the present work, an improved methodology for the optimization of fiber reinforced composite materials to maximize the load carrying capacity via the layer-wise tailoring of fiber orientations, fiber volume fraction, and layers' thickness is suggested. The classical lamination theory is used to determine the lamina stresses for thin laminates subjected to force and/or moment resultants and the first-ply failure load is obtained using the Tsai–Wu failure criterion. An integer-coded GA, based on the elitist non-dominated sorting GA [37], is implemented to obtain optimal designs for conflicting objective.It keeps track of the number of new designs that are added to a historical archive of non-dominated individuals and terminates the algorithm when it reaches the point of diminishing returns. FEA applied on the optimized structure to find maximal von mises stress on the plate. .

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2. Problem Methodology

In the shown figure, a rectangular Cartesian coordinate system x, y and z is used to represent the infinitesimal deformations of an N-layer laminated composite material. in the unstressed reference configuration. The total thickness of the laminate is t_p and the bottom and top surfaces are located at z = -$t_p/2$ and $t_p/2$, respectively. Lamina n consists of a macroscopically homogeneous fiber-reinforced composite material with fiber volume fraction $V_f^{(n)}$, extending from $z^{(n-1)}$ to $z^{(n)}$ in the z-direction. The principal fiber direction is oriented at an angle of $\varphi^{(n)}$ to the x-axis.

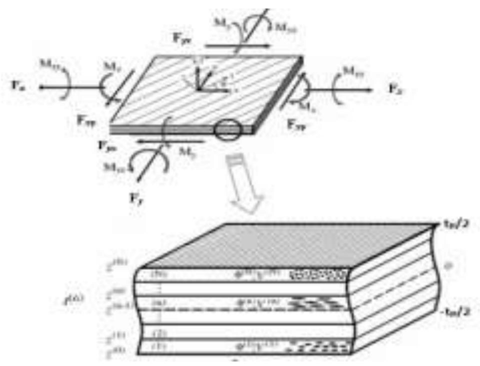

Fig. 1: Representation of a thin laminated composite plate subjected to force and moment resultants, with a close-up view of the plate's cross section.

Analyzing the current model by Classical lamination theory (CLT) is applied in case of continuous fiber laminated composite. Derivations of CLT follow the classical procedures cited in earlier publications [38]. Tsai–Wu failure criterion has been applied to analyze the failure of laminated composite plate to obtain a safe design.

The algorithm systematically analyzes each individual in the population of designs according to set specifications and assigns it a fitness rating which reflects the designer's goals. This fitness rating is then used to distinguish structural designs that perform better than others, thereby enabling the GA to eliminate the weak designs using the reproduction operator. The remaining, more desirable genetic material is then utilized to create a new population of individuals. This is performed by applying two more operators similar to natural genetic processes, namely gene crossover and gene mutation as in Fig.2 [39-40].

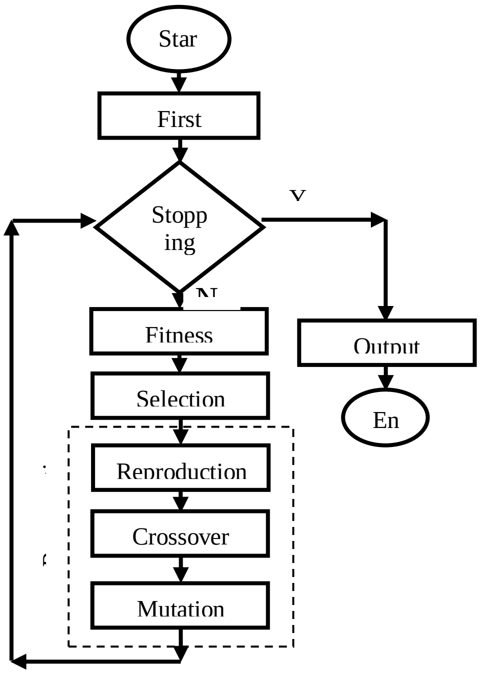

Fig.2: Genetic algorithm basic steps.

The process is iterated over many generations in order to obtain optimal designs. The evolutionary technique provides major benefits over traditional gradient-based optimization routines, such as nominal insensitivity to problem complexity and the ability to seek out global rather than local optima.

A real-valued array which consists of the fiber volume fractions, $V_f^{(n)}$, fiber orientations, $\varphi^{(n)}$,and thicknesses, $t^{(n)}$, of the laminae can be used to produce a laminate design, x, represented by the following equation:

$$x = \left\{ \left\{ V_f^{(1)}, V_f^{(2)}, ..., V_f^{(N_{max})} \right\}, \left\{ \varphi^{(1)}, \varphi^{(2)}, ..., \varphi^{(N_{max})} \right\}, \left\{ t^{(1)}, t^{(2)}, ..., t^{(N_{max})} \right\} \right\}$$

According to the laminate design equation, there are $3N_{max}$ decision variables. It is possible for some of the laminae to have thicknesses equal to zero, in which case the corresponding volume fractions, fiber orientations and thicknesses are simply deleted from the array y. If there are N_{zero} laminae that have zero thickness, then the laminate consists of $N = N_{max} - N_{zero}$ laminae of finite thicknesses.

An optimization problem is stated in the following form:

$$\begin{aligned} &Find && x \\ &Maximize && F(x) \\ &subject\ \ to && g_m(x) \le 0 \qquad m = 1,2,\ldots, M \end{aligned} \qquad (2)$$

Where F(x) is the objective function and $g_m(x)$ are the M constraints.

Minimization of one or more objective functions needs multiplying those objective function by (-1) to transform it into one where all objective functions are maximized. Only inequality constraints can be handled in problem [39].

2.1 Genetic coding:-

In current problem for getting optimal design of laminates, integers represent the individual decision variables as follows:

$$x = \left\{\left\{v^{(1)}, v^{(2)}, \ldots, v^{(N_{max})}\right\}, \left\{\theta^{(1)}, \theta^{(2)}, \ldots, \theta^{(N_{max})}\right\}, \left\{\eta^{(1)}, \eta^{(2)}, \ldots, \eta^{(N_{max})}\right\}\right\} \qquad (3)$$

where $v^{(n)}$, $\theta^{(n)}$ and $\eta^{(n)}$ are integers ranging from 0 to N_V, 0 to N_φ and 0 to N_t, and the transformations from integer coded values to the decision variables are,

$$\begin{aligned} V_f^{(n)} &= \frac{v^{(n)}}{N_{V_f}}\left(V_{f\,max} - V_{f\,min}\right) + V_{f\,min}, \\ \theta^{(n)} &= \frac{\theta^{(n)}}{N_\varphi}\left(\varphi_{max} - \varphi_{min}\right) + \left[\varphi_{min}\right], \\ t^{(n)} &= \frac{\eta^{(n)}}{Nt}\left(t_{max} - t_{min}\right) + t_{min}, \end{aligned} \qquad (4)$$

2.2 Genetic algorithm:-

Suggested integer-coded version of the non-dominated sorting GA (NSGA-II) is used to obtain the optimal design [27]. The NSGA-II algorithm is altered to include an archive of the historically non-dominated individuals (Ht). A schematic of the process is used to update the parent population (Pt), child population (Qt), and historical archive of non-dominated solutions (Ht), from generation t to t +1 is shown in Fig. 3.

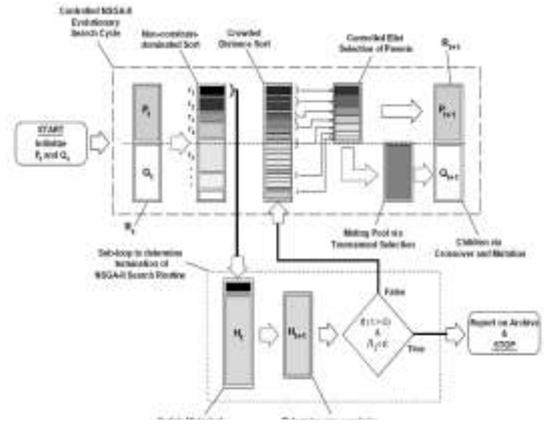

Fig.3: Schematic of the controlled elitist NSGA II multi-criteria GA with termination criteria based on a non-constrain-dominated historical archive.

3. Optimization Problem Formulation:-

3.1 Problem objective function:-

The objective function can be stated as follows:

$$\sigma_f = \min_{z \in \left[-\frac{t}{2}, \frac{t}{2}\right]} \left[\min\left(\left|\sigma_a + \sigma_b^+\right|, \left|\sigma_a + \sigma_b^-\right|\right)\right] \quad (5)$$

Under different sources of loading which can be categorized as follows:

- Bending loads,
- Peak stress loads

3.2 Bending loads constraints

Pure bending is achieved in the middle section of the plate without the presence of transverse shear stresses. Stress, strain, and Young's modulus can be calculated as well, in addition to structural stiffness of the bone. A study conducted on healing metatarsal bone nine weeks after surgery evaluated its bending stiffness and showed that bending stiffness increased in plate with smaller gap sizes and higher fixation stability [34].

The bending stiffness (bending moment/angulations) and flexural strength of composite bone plates fabricated by various forming conditions were compared. The bending stiffness (BS) and the flexural strength (σf) were calculated by the following formulae.

$$BS = \frac{M}{\theta} \qquad (6)$$

$$M = \frac{p}{2} l \quad (7)$$

$$\theta = \tan^{-1}\left(\frac{\delta_1}{l}\right) * \frac{180}{\pi} \quad (8)$$

$$\sigma f = \frac{\text{Mmax} * y}{I} \quad (9)$$

$$y = \frac{2r_1}{3}\left(\frac{\sin^3 \alpha_1}{\alpha_1 - \sin \alpha_1 \cos \alpha_1}\right) + \left(\frac{t}{2}\right) - \frac{2r_2}{3}\left(\frac{\sin^3 \alpha_2}{\alpha_2 - \sin \alpha_2 \cos \alpha_2}\right) \quad (10)$$

$$I = \frac{r_1^4}{4}(\alpha_1 - \sin \alpha_1 \cos \alpha_1 + 2 \sin^3 \alpha_1 \cos \alpha_1) + \frac{bt^3}{12} - \frac{r_2^4}{4}(\alpha_2 - \sin \alpha_2 \cos \alpha_2 + 2 \sin^3 \alpha_2 \cos \alpha_2) \quad (11)$$

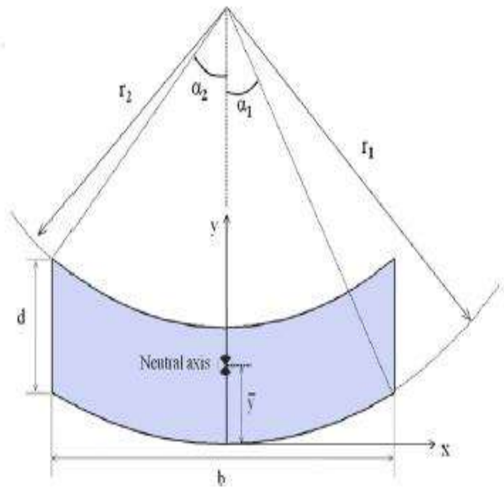

Fig.4: bending moment calculation

3.3 Peak stress load constraints

The bone and plate weights generate alternating tensile and compressive forces along the length of the plate that can be calculated using the following formula.

$$\sigma max = \frac{(F\iota w)}{(16I)} \quad (12)$$

The total vertical displacement:-

$$\delta_{max} = \left(\frac{F\iota^2}{192EI}\right) + \frac{\sqrt{2}}{2}\left(\frac{\sqrt{2}\, F\iota^2}{EI} + \frac{F\iota^2}{2EI}\right) \quad (13)$$

3.4 Manufacturing constraint

Manufacturing constraints can be defined using the following formulas:-

$$0.5 \le V_f \le 0.7 \quad (14)$$

$$0.01 \le t \le t_p \quad (15)$$

$$-90^0 \le \varphi \le 90^0 \quad (16)$$

4. Problem Modeling

In the present study, the structure of conventional bone plate made off stainless steel 116L whose mechanical properties mentioned in table (1) can be used to find the composite structure of a composite plate has the same dimensions of the original pate. The plate's type is dynamic compression plate (DCP) which can be used to fix tibia fractures.

Table (1): Material properties of current structure

Material	ρ (g/cm^3)	E (GPa)	Poisson ratio	G (Gpa)
SS 316L	8000	193	0.3	77

DCP has six counter sink holes used for fixing plate on bone using six screws. Dimensions of current model of plate were cleared in Fig.5 and table (2). Fig.6 shows a real view of plate and its how to fix bone fragments. this plate resist under normal force equal to the weight of bone that result in bending moment causing bending and peak stress.

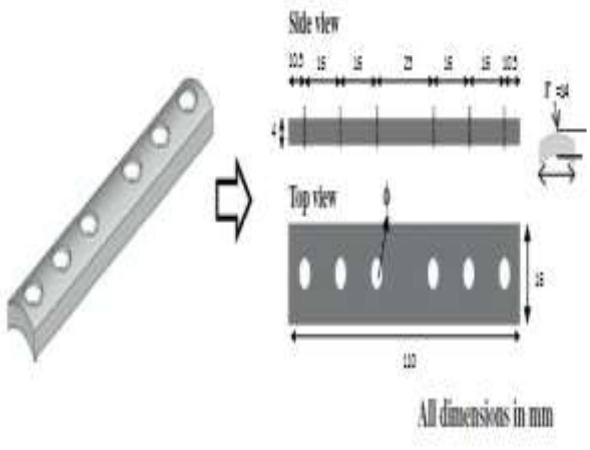

Fig.5: Current structure diagram

Fig.6: Photo of a real one used in treating bone fracture.

Table. (2): Dimension current plate model

Dimension definition &Symbol	Value (mm)	Dimension definition &Symbol	Value (mm)
Total length (L)	110	Hole diameter	4
Thickness (t_p)	4	Distance between holes	16
Width (d)	16	Distance between 3rd and 4th screw	25
Number of holes	6	Screw length	25

5. Numerical Analysis

To test the performance of the new optimized design of plate, tibia plate was simulated. Static compression, which is caused by patient weight, was considered as the loading condition.

5.1. Procedure

The following considerations were taken while constructing the geometric model of the problem:-

- Plate was dimensioned using a six-hole narrow dynamic compression plate (DCP), but the holes were drilled as in neutralization bone plates. This is because better results were obtained with the use of them in human cases (1). Also, although the reference plate was 4 mm in thickness, in order to ease the compositeplate configurations, plate thickness in the model was taken as 4 mm. Thus, 5 laminae were easily configured symmetrically to form the composite plates
- Plate was modeled as it was under bending and compression, the case of torsion was eliminated.
- Compression which is considered as the loading condition of the problem was thought to be caused by theweight of the patient while standing up. The compression load was assumed as:

  Compression force (F) = 800 N
  Area of plate = 16 *4 = 64 mm^2
- Smooth transverse fracture with 4- mm gap was considered in the middle of the bone.
- The geometrical model was formed to be fixed from one side and free from the other side.

5.2. Materials:-

Glass fiber reinforced Polyvinyl Cholride (PVC) matrix laminates have been considered for composites of plate. Plate consists of 5 layers; these layers have different volume fractions, orientations, and thickness. Mechanical properties of the composite plate were mentioned in table (3). Volume fraction and orientations of layers consisting plate resulted in table (4).

Table (3): Mechanical properties of selected fiber and matrix

Property	Glass fibers(E-glass)	PVC matrix
E_1 (GPa)	76.0	3.3
E_2 (GPa)	8.7	3.0
G12 (GPa)	3.24	1.0
ν_{12}	0.30	0.40
S_{ut} (MPa)	2600	52
S_{uc}(MPa)	2360	-214
S_{us}(MPa)	-	72.0
ρ (Kg/m3)	2540	1470

5.3. Analysis:

The finite element analysis was performed regarding the above considerations using Cosmos[R]. Composite plate analysis was performed by the use of angle-ply laminate configuration because these configurations give the best results than unidirectional and other configurations. Shell 4L element is selected with six degree of freedom per node.

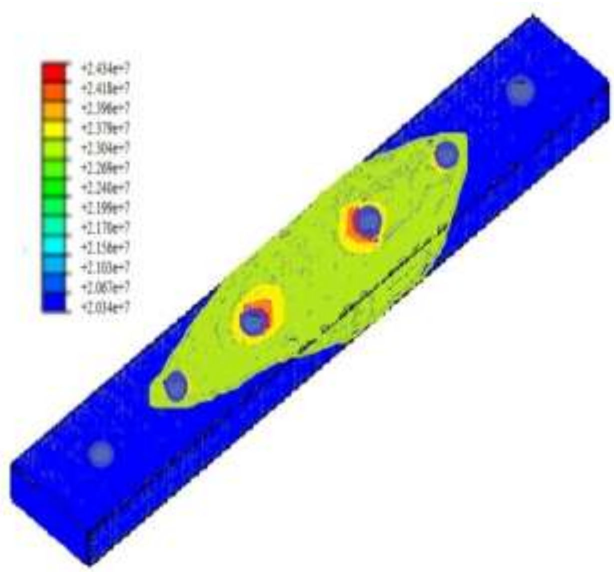

Fig.7: Von mises stress on composite plate.

6.1 Results:

For achieving better healing performance of a particular fracture configuration, an appropriatebone plate material should be selected before surgery. Quantitative computer simulations were used for determining the parameter that most significantly influenced the healing performance. Genetic algorithms used to find the optimum design of acomposite bone plate used to treat tibial fracture. The optimization parameters were fiber volume fraction, angulation and thickness of each layer included in the plate. Finite element analysis was used to simulate the plate and test it under compression load and its resultant m0ment. The maximal von mises stress was calculated.

6.1. Optimization Results:-

In this section of research, the results of optimal design studies performed on considered models have been introduced. The lamina thickness $t_p(n)$ can vary from t_{min}= 0 to t_{max}= t_p. Optimal values are sought for the V_f, φ and t_p. The GA parameters were tuned by studying the convergence of the algorithm for the model problems. It was found that controlled elitism enhanced the ability for the algorithm to seek out the entire optimal front. In consideration of the overall accuracy of the search versus computation time, the termination criterion parameters are chosen to be G = 120generations, ε = 0.005 and δ = 0.005. That is, the algorithm is terminated when it is unable to find a single, new, historically non-dominated, less crowded solution over a span of 120 generations that changes the average crowding distance of the historical archive by 0.5%.

Glass fiber reinforced Polyvinyl Cholride (PVC) matrix laminates have been considered. Mechanical properties of the constituent materials are provided in Table (3).

By enacting optimization model, the optimum number of layers is found to be equal to 5 layers. Table (4) shows the 5 layersV_f ,θ, and t_p.

Table (4): Optimum design for composite plate structure

Optimization variables	**Layer 1**	**Layer 2**	**Layer 3**	**Layer 4**	**Layer 5**
t_p	1.26	1.00	0.86	0.48	0.40
θ	+26	-18	-5	+42	-35
V_f	0.70	.67	0.62	0.58	0.54

6.2. Numerical Analysis Results:-

Finite element analysis of bone plate were conducted for the above mentioned implant material. The results were implemented for computing maximum von mises stress on plate and its location on plate. The von mises stress on the plate was calculated and shown in (Fig.7).The maximum von mises stress is equal to 2.434 * 10^7 as shown in Fig.7. The maximum von mises stress locates at the third and fourth screws because the fracture gap locates between these two screws and the fracture type is transverse with 4-mm length. Difference between maximum and minimum stress is about 0.4 * 10^7. It is obviously clear that stress distribution is smooth on the plate. The maximum stress applied on composite plate consists of Glass fiber reinforced Polyvinyl Cholride (PVC) matrix laminates is lower than maximum stress on metallic plate that calculated by M. O. Kaman.et.al in 2014 [42] and it is also lower than the stress of composite plate that consists of carbon/epoxy fabric composite and a glass/polypropylene fabric composite (Twintex, TW-22-P, jb martin, France) computed by Hyun-Jun Kim, et.al. in 2011 [43]. Table (5) compare numerically the von misesstresss of conventional plate made of metals (Ti6Al4V, SS) with the suggested composite plate. The amount of reduction in weight and stress on the plate is also calculated

Table (5): Von mises stress for different plate materials.

Properties	Material				
	Glass fibres/ PVC matrix	Titanium alloy Ti6Al4V	Reduction Percent	Stainless Steel 316L	Reduction Percent
Weight (g)	15.9	31.19	49 %	56.32	71 %
Yield strength	1380	880	---	205	---
Stress (MPa)	2.434	5.0476	52 %	6.3358	61.5 %

7. Conclusion:-

This study introduced a methodology to find the optimum design of a laminated bone plate fabricated from composite materials. Fibre orientations, fibre volume fractions, layer thickness and number of layers are chosen as the optimization variables. The layer wise material properties are estimated using simplified micromechanics equations.

An integer-coded genetic algorithm has been extended to include an archive of the historical non-constrain dominated set, which is updated at each generation. The historical archive is used in conjunction with a crowded distance metric to obtain a termination criterion that automatically stops the algorithm when the moving average of the number of new, less crowded, non-constrain-dominated designs added to the historical non-constrain-dominated set falls below a specified entry value.

In the problem model, the layer wise fiber orientations and the volume fractions are tailored to maximize the load carrying capacity and minimize the mass of laminated glass fibers/PVC matrix subjected to bending moments. The plate is subjected to axial load in the same direction and bending load.

FEA is also performed to evaluate the von mises stress on the plate to test it. After performing analysis and comparing the value of von mises stress on plate with other plate materials, it was found the von mises stress on composite plate reduced by52 % than titanium plate and 61.5 % than stainless steel plate. This reduction in stress leads to more stability in fixation and enhanced healing rate.

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