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Finite Element Analysis of Tube Rigger of a Single Scull Rowing Boat

Dr. Vishwanath Karad, Kirit Kokje, Pushkaraj D. Sonawane, Dr.Mrudula Kulkarni

MIT World Peace University Pune India

Email: kititkokaje@gmail.com

Abstract: For a single scull rowing boat, rigger is the main component. The forces applied on oar by the oarsman is transmitted on the boat shell via rigger. Thus rigger should be enough sturdy and long lasting component of the rowing boat. Currently tube riggers which are attached to the boats are manufactured locally. The stress analysis of these riggers was not found in the literature. This paper is about the FEM stress analysis of the traditional tube rigger used for rowing boats. Also it discusses the issues raised by oarsman who are the users of these tube rigger. Starting from the real measurement, CAD model of traditional tube rigger is done. From the literature, amount of force acting on the rigger by the oarsperson is obtained. Finite Element Analysis of this rigger is performed in ANSYS R16.0. The FEM analysis gives us values of stresses induced in the rigger. These values are compared for permissible limits of material of rigger. Thus induced stresses are within safe limits. This will help in further improvement in design and may also be helpful for the local manufacturers to have scientifically designed and tested rigger. The FEM analysis verified that the stress induced in tube rigger is within the permissible limits. Thus tube rigger is safe as per its current dimensions and the selected materials.

Key words – Rowing, Rigger, FEM stress analysis, Racing Boat, Sports equipment

INTRODUCTION

Rowing is the propulsion of a racing boat, with or without coxswain, by the muscular force of one or more rowers, using oars as simple levers of the second order and such that boat moves backwards. Rowing on a machine or in a small water body without moving boat, which simulates the action of rowing in a boat is also considered as rowing. In a rowing boat, except the slide (moving seat), all load bearing parts such as riggers, tholl pin etc. including the axes of moving parts, must be firmly fixed to the body of the boat.

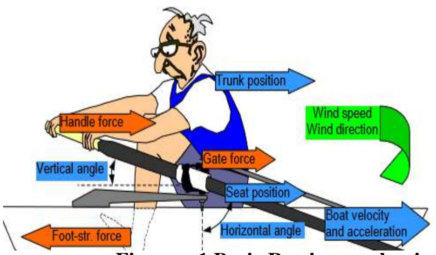

Figure – 1 Basic Rowing mechanism

The two main stages of rowing stroke are Drive and Recovery.

1. Drive - The drive, also called as stroke, is the phase from the catch (oar enters the water) to the extraction (oar comes out of water).

- On entering the oar blade in the water at the catch, the oarsman drives the boat with oar by straightening the legs while the body remains leaned forward and the arms straight. This is called the *leg drive*.
- The oarsman continues kick further by legs and also starts putting additional power by opening up his or her back towards the bow end of the boat.
- After completion of leg drive, leg becomes flat to the boat shell, the rower pulls oar further by opening up his or her back towards the bow end. Thus arms bring the oar(s) to his chest. This is called *the draw*. Rower lean behind a little and then elbows bend.
- When oars are pressed down by hands, as a lever, oars come out of water.
- After withdrawal of oar from water, oar is turned by 90 degree so that again it becomes horizontal. Hands are straight in elbow and rower sits upright. It is termed as *feathering*.
- Rower attains an initial position as the beginning, body leaning back, hands are straight clearing knees, and legs straight.

2. Recovery - The recovery is after drive is completed.

- After completing the stroke, the oars person has body leaning back, legs straight and arms are near belly. Now the *recovery* or *the slide* begins.
- The rower brings the hands forward making them straight pushing the oar away from belly while, maintaining the oar at a constant level with his or her legs straight, and body leaning back.
- The rower bends in little forward to around 30 degrees to vertical, maintaining the oar level. Legs are still straight and keeping the back straight. This part of the recovery is may be called as "body prep".
- The rower bends the knees and come forward by using the slide having rollers. Oar are still at same level.
- Sometimes during sliding forward, the rower turns the oar handle(s), making the face of the blade to be at right angle to the water. This is called *squaring* or *rolling up* the blade. It is done after the handle clears the ankles and may differ from rower to rower.
- After getting at the front of slide, further forward motion is not possible. So at this front stop i.e. at the end of the recovery, and the knees up ready to kick, the blade is quickly and easily put into the water by a slight raising of the hands. This is called the *catch*.

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LITERATURE REVIEW

In the past several researchers have studied, though Rowing is a sports, lot of engineering comes in picture when it comes to the Olympic level game. The equipment design is very much essential to have best performance! Lot of research is being done regarding improvement of equipment and analysis of the forces applied on it.

A paper by Dr. Valery Keshnev - Rowing Biomechanics: Technology and Techniques 2004 [1] is about Biomechanical measurements, Rowing Kinetics, Biomechanical analysis. This methodological set-up puts practical aspects on the top of the pyramid and makes them the most important part of the system, which requirements should be considered at the earliest stages of any research and development project.

Chris Pulman - The Rowing Physics – Gonville & Caius College, University of Cambridge. [2] In this literature, the motion of rowing and competitive boats has been discussed. The methods of propulsion, while obtained from the motion of the oarsman along with the complex drag forces are changing as per conditions. The mechanics behind the rowing action are put in the form of equations which are the basics for force analysis of the Rowing action.

C J F P Jones and C J N Miller - THE MECHANICS AND BIOMECHANICS OF ROWING - Newcastle University – year 2002. [3] These are Notes provided as part of a Coaching Evening York City Rowing Club, 20th January 2002 which are still are very useful. An alternative method of removing or reducing the effects of crew momentum on the motion of the boat is through changes in boat design, such that the crew is not required to move relative to the boat. This can be accomplished by replacing the sliding seat by the sliding rigger. As the riggers of a boat are considerably lighter than the crew, the momentum of rigger motion comparative to the boat will not be much.

B. K. FILTER - Design and materials in rowing - Germany. [4] This is regarding rules and regulations which are allowed in Rowing. In 1979, the International Federation of Rowing Associations (**FISA**) formed a technical board to check and control the development of rowing equipments. The FISA rules concerning equipment for rowing focus on fairness of competition and the safety of the athletes taking part. In Sections 11.2.1-11.2.4 indented material is taken from the 2006 FISA Rulebook. The manufacturing, dimensions and design of the rowing equipments shall be within the bounds laid down in Rules. The board of FISA impose appropriate requirements by their rules and regulations.

Win Tech Brochure – year 2013. [5] This is the world's leaders in the boating equipment manufacturing industry. Win Tech Racing's mission is to increase the performance of all levels by facilitating the growth of boating by making the purchase of quality enclosures easier and more affordable. They claim that their products are designed in Germany and manufactured and delivered to us by the world's largest and most advanced shipyards, promising to provide long-term excellence in service and support. Win Tech Racing has established an international organization (IO) dedicated to the innovation of racing shell manufacturing, investing in research and development to bring the latest advances in design and technology, maintaining the best price-value relationship in the market, by providing superior service and supporting their global distribution.

METHODOLOGY

The traditional riggers attached to the boat is the main component of the boat which takes the force from oar and transmits it to the shell of the boat. CAD model of the same is made by using the actual measurements. As rigger is the main force bearing element, it shall be sufficiently robust in design. So there is no much scope in optimization and weight reduction in the design. Also there is no mass production and hence no much benefit of saving some small cost factor. For finding the stresses produced in the rigger, the forces applied on the gate pin are to be found out. Gate pin is attached to the rigger firmly and forces applied on the oar during the stroke are taken up by gate pin and ultimately to the rigger.

DESIGN CONSIDERATIONS&BASICS OF MECHANICS

The basic principles of the forward motion of a boat are, may be complicated by the changeability of the centre of mass (CM) of the rowers caused by the slides (fig. 2). When the oars are dipped in the water, this transmits to the momentum conveyed to the water. In the recovery phase, when the oars are feathering in air and the rowers slides forward, momentum conservation (equation) requires that the boat surges forwards. This motion can be seen while observing a rowing boat.

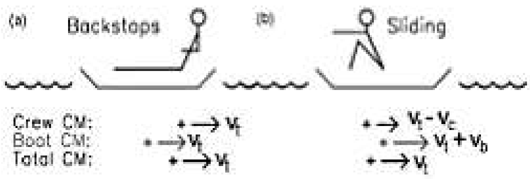

Figure – 2: Rower position during stroke (a) Back stop and (b) Sliding [2]

The fundamental ideologies of the forward motion of a boat

$$m_c v_t + m_b v_t = m_c(v_t - v_c) + m_b(v_t - v_b) \quad \text{……………… (1)}$$

where,

m_c, v_c, m_b and v_b are the masses and velocities of the crew and the boat and

v_t is the boat speed instantly after the blades are out of the water.

Thus we can say that

$$v_b = \frac{m_c}{m_b} v_c \quad \text{………………… (2)}$$

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This velocity of boat is imparted to it by the action of oar which are inside the water and pulled by rower. Hence we can consider the forces exerted on it by the simple liver attached at the oar lock as shown. We need to calculate these forces as the total force is going to act on the rigger which acts like a truss to support this force and propel the boat.

The force E is put at the oar handle, but the blade behaves like the pivot. Due to this, the force at the rigger (L) is moved.

Thus

E*b = L*a

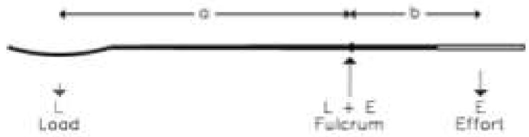


Figure- 3 Forces applied on the Oar [2]

The Rowing stroke analysis,

The function of the stroke is to transfer the work done by the rowers into kinetic energy of the boat. The mechanisms behind this transfer of momentum, however, are relatively complex. In fact, in the rowing world, it has been the subject of controversy about the exact interaction of the blade with water. It is generally accepted that, at the beginning and end of the stroke, lift – acting in a horizontal direction - provides the main impetus for propulsion. However, during the middle of the stroke the resistance of water on the blade provides propulsion. It is not clear which of these mechanisms is predominant.

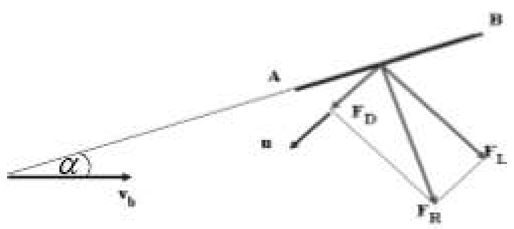


Figure – 4: FBD of the oar. AB is the blade, u is the velocity of the water, α is the angle made by the oar with the side of the boat, v_b is the velocity of the boat and F_R is the force acting on the blade resulting from the drag (F_D) and the lift (F_L) forces [2]

At shallow angles α (fig. 6), the blade acts like a hydrofoil and the resultant force on the blade is made up of a drag force F_D and a lift force F_L. As water is directed to one side of the blade a reaction force results - the lift. In contrast to an aeroplane wing, the flow of the water around the blade results in the lift force acting horizontally, rather than vertically. The lift force does zero work, so if it is maximized while the drag force is minimized then little energy is wasted and the boat moves more quickly. Under these conditions, however, the longitudinal component propelling the boat is rather small. It has been proposed by Brearley (1998) and van Holst (2004) that altering the angle of attack (fig.) would maximize this effect in the first part of the stroke but have a negative effect in the latter part.

If the rowers aim to produce peak power at the start of the stroke altering this angle may give an advantage, while this is not much energetically efficient (fig. 2). The drag and lift forces are

The resistances are

$$F_D = \frac{1}{2} C_D \rho A v^2$$

$$F_L = \frac{1}{2} C_L \rho A v^2$$

…………………. (3)

Where C_D and C_L are the drag and lift coefficients and v is the velocity of the undisturbed flow. The directions of F_L and F_D are determined by the direction of circulation of the vortices. It can also be seen from fig. that the C_D and C_L are related by

$C_D / C_L = \tan \alpha$. ……………………. (4)

As α increases throughout the stroke F_D increases and the lift decreases until $\alpha \approx 40^o$ when the blade stalls in the water – in the same way an aeroplane stalls in the air - and lift is zero. At this point resistance against the blade through the exchange of momentum with the water provides the mechanism for propulsion. When α increases to approximately 110^o the blade again begins to experience lift until the end of the stroke. Thus theoretically this can help to find the forces acting on the rigger. Practically forces are measured by using transducers

ROWING KINEMATICS

OAR ANGLE: Since the horizontal pitch angle is used to define the phase of the rowing stroke, the pitch angle will be studied first. (figure 1). Two different coordinate systems of the pitch angle are used: the first defines zero degrees with respect to the ship axis at the vertical position of the paddle, and the second identifies zero degrees when the paddle is parallel to the ship axis. Here, the first coordinate system will be used. In this system, the pitch angle at the capture has a negative value and is at a positive release value. We define the beginning of the stroke cycle when the paddle (vertical position) is at zero during recovery. The capture angle is defined as the minimum value and the release angle is the maximum.

(a) Transducer for handle force measurement

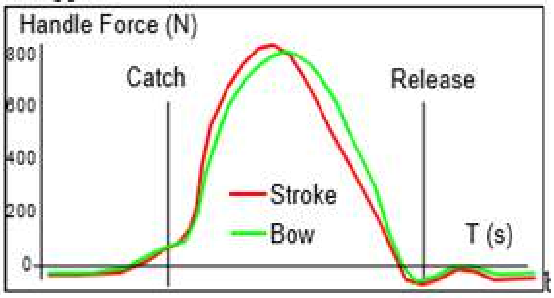


Fig – 5 (b) data example for a pair [1]

Although the horizontal pitch angle is one of the most traditional measurements in boating, we have recently introduced the measurement of the vertical pitch angle. The device for measuring two angles (Fig. 7, a) consists of two servo potentiometers. The first potentiometer measures the horizontal angle which is mounted on top of the pin. The other potentiometer is connected to the first potentiometer and measures the angle in vertical direction. When the center of the blade is at the water level, it reads zero degrees. The light hard rod is attached on the body of the second potentiometer, which is connected to the paddle shaft.

HANDLE AND GATE FORCES

The handle shaft can be measured by a precision inductive or strain gauge sensor to measure the pitch of the paddle shaft (Fig. 7, a). The disadvantage of this method is that it depends on the characteristics of the paddle shaft and requires calibration for each particular paddle. In addition, using the paddle bending we actually measured the handle torque (torque M), and if we know the length of applied lever, we can derive the force. However, the point at which the handle force is applied is uncertain, especially in rowing boating, where the rower can be pulled more with the medial or lateral arms. If we are interested in the handle force (F_h) itself, this can cause problems, but it will produce a more reliable rowing force (P_h) value acting at the handle, because:

$P_h = \omega * M$ ……………………….. (5)

Where ω is the oar angular velocity.

We can see here that the handle power does not depend on the inboard and, therefore, not on the point of the force application.

a) **Foot-stretcher force transducer**

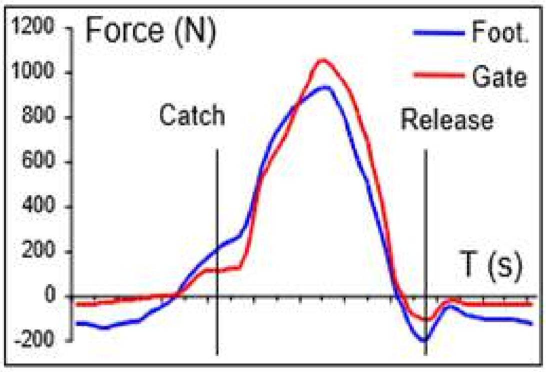


Figure 6: (b) Data example [1]

Different types of instrument doors can be used to measure the door force. Up to three force components (forward, lateral and vertical) can be measured relative to the ship or paddle.

This method produces more accurate and informative data on the force applied to the boat, which can be useful for a precise calculation of the net propulsive force for each rower. However, calculation of the handle power (P) from the gate force (F_g), depends on the inboard and outboard (R_{out}) lever and, consequently, on the knowledge of the points of the handle and blade forces applications:

$$P = w * R_{in} * F_h = w * F_g * (R_{in} * R_{out}) / (R_{in} + R_{out}) \quad \text{…………………..} (6)$$

The outboard lever Rout in this equation changes during the drive, since the point of application of the blade force resultant moves on the blade (Nolte 1985, 163, our unpublished data). Therefore, the gate force measurement does not allow an accurate estimation of the power production of the rower. The software allows the derivation of selected parameters for each stroke (Figure 9). This is useful for an analysis of the rowers' performance during the race.

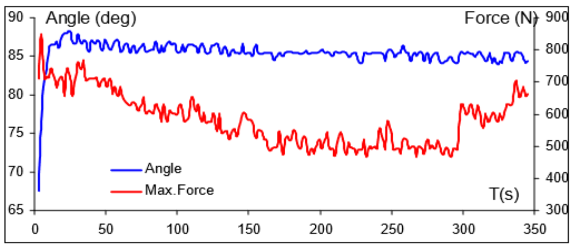


Figure 7: Graphs of the total oar angle and maximum force over a complete rowing race [1]

STATISTICAL ANALYSIS AND EVALUATION

Having large samples of biomechanical information stored in a database, it is easy to perform a statistical analysis with the purpose of assessing each rower relative to a similar group of rowers. We use MS Access™ database for data storage. After three years of testing the database has more than 400 session records, 1800 boat-samples and 6000 rower-samples. Figure shows an example of a table for the evaluation of the biomechanical parameters. The values in the table are based on the average (Average = A = middle column for each parameter) and standard deviation SD in each rower's group.

The "very low" interval of each parameter is chosen in a range below A–2SD, "Low" is between A-2SD and A-SD, "High" is between A+SD and A+2SD, and "Very high" is above A+2SD.

A more sophisticated statistical analysis can be done with the purposes of correlating biomechanical parameters and assessing their differences in groups of athletes with various skill level, etc.

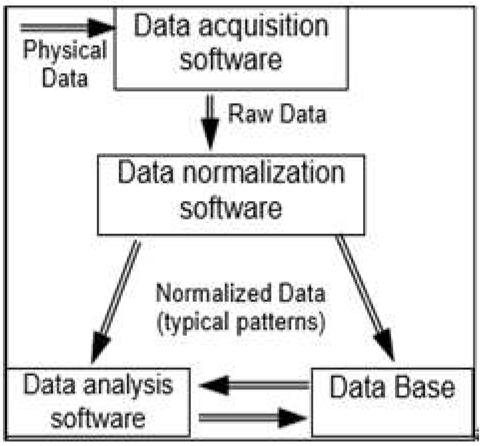
For example, it was found that the blade propulsive efficiency correlates with the shape of the force curve (unpublished data), or that higher qualified rowers have higher percentage of the trunk power.

Table -1 Evaluation table of the biomechanical parameters in rowing [1]

Rowers' Groups	n	Total Angle (degrees)					Maximal Handle Force (N)				
		Very Low (Less Than)	Low (Less Than)	Average	High (More Than)	Very High (More Than)	Very Low (Less than)	Low (Less than)	Average	High (More than)	Very High (More than)
Men Scull	519	102.8	106.6	110.4	114.2	118.0	593	680	766	853	940
Men Light Scull	161	99.5	103.3	107.1	110.9	114.8	579	636	692	749	805
Men Sweep	1628	84.4	87.8	91.2	94.6	98.0	491	581	671	761	850
Men Light Sweep	808	81.0	84.5	87.9	91.4	94.9	467	528	590	652	714
Women Scull	489	96.7	101.0	105.2	109.4	113.7	394	471	547	624	701
W. Light Scull	739	95.2	99.7	104.2	108.7	113.2	355	416	477	538	599
Women Sweep	1708	80.0	83.5	86.9	90.4	93.8	345	412	479	547	614

DATA ACQUISITION SYSTEM

Rowing is the cyclic sport. This means that athletes perform a number of stroke cycles during the event (around 250 during a 2000m race). While modern computer equipment makes it technically possible to process and output such amount of information, it would be practically meaningless for rowers and coaches. Therefore, the main task of data processing is its conversion into a form, which represents one typical stroke cycle. We call this process normalization. Figure represents telemetry software structure and illustrates data normalization process.



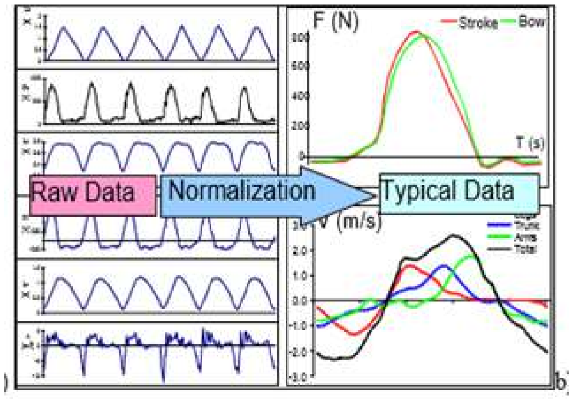


Figure – 8 Block-schemes of rowing software (a) and data processing (b) [1]

The main features of our normalization algorithm are:

- All data is normalized relative to the average cycle time over the sampling period (cycles deviating more than a certain percentage from the time of the average cycle are rejected).
- The stroke rower's time of the cycle start is chosen as the trigger for the whole crew.
- Each set of normalized data was then calculated to 50 data points. This amount of points per stoke cycle was chosen as a compromise between data accuracy and volume.
- The average value and its standard deviation are derived for each point of each array.

This means that we derived a normalized set of 50 data points for each measurement (oar angle, gate force etc.) representing the average stroke characteristics. We have checked the validity of the algorithm by means of a comparison of the extreme values (such as catch and release angles, max. force, work and power, etc.), which were calculated using normalized data with ones taken as an average from each stroke cycle. The differences were in a range 0.02-0.85%, this is considered satisfactory for a biomechanical analysis in rowing.

FEM ANALYSIS

Theoretically as well as experimentally it is found that maximum force acting on the rigger is around 766 to 900N at the dynamic phase of race in a single scull racing boat. Considering factor of safety (including effect of instantaneous impact) in the range of 1.2 to 1.5 taking the design load to be 1500N. The FEM tool used in ANSYS version 16.0 .In ANSYS, 3 D CAD model of traditional tube rigger is made. It is modelled as truss member. The material property of high strength aluminum alloy is 70 GPA and poisons ratio is 0.29. This is the metal used for sports equipment as approved by world sports equipment manufacturing standards.

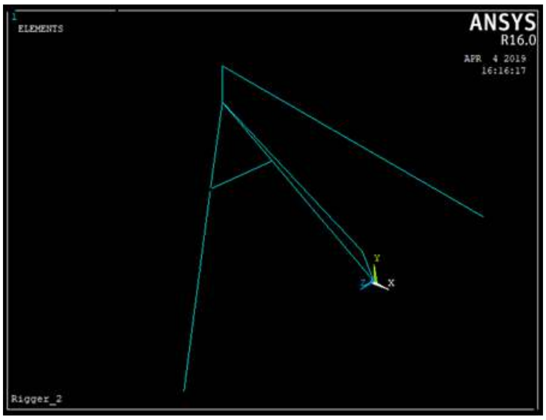


Fig 9: (a) 1 D CAD model of rigger

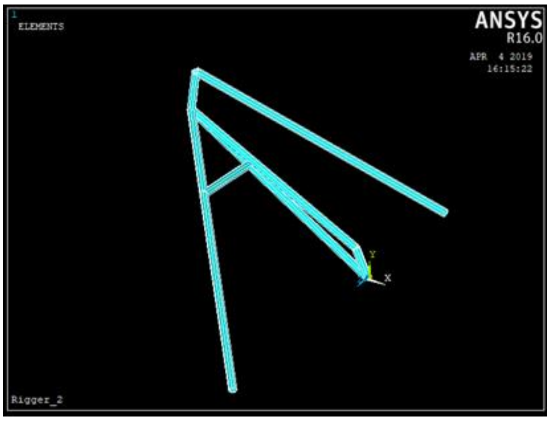


Fig 9 (b) FEM model after assigning properties

The model is meshed with Element type Beam 188 from ANSYS library with degree of freedom six, typically .,U,V,W, θx, θy, θz .This element allows us to create circular section of pipe with desired thickness. Meshing is done with triangular mesh with controlled mesh density. The meshing is reviewed for badly shaped elements if any and remeshing is carried out. The loads and constraints are applied on meshed model. Force of 1500N is applied along Z axis which is taken parallel to the central axis of the boat as shown in figure 1. The static structural analysis is run. After the solution is complete, the results are stored in general post processor, in the form of list and Contours. Some typical results of importance are retrieved as images and presented below.

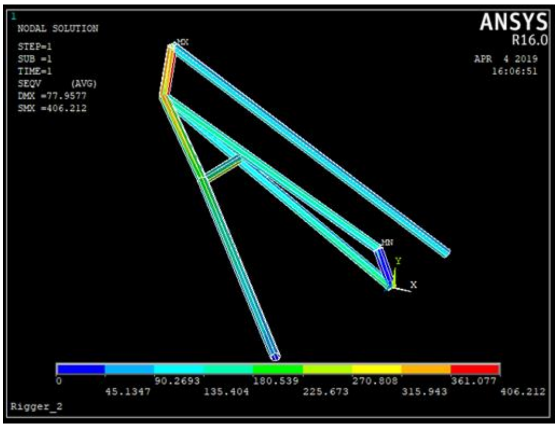


Fig 10: (a) Von Mises Stress countour

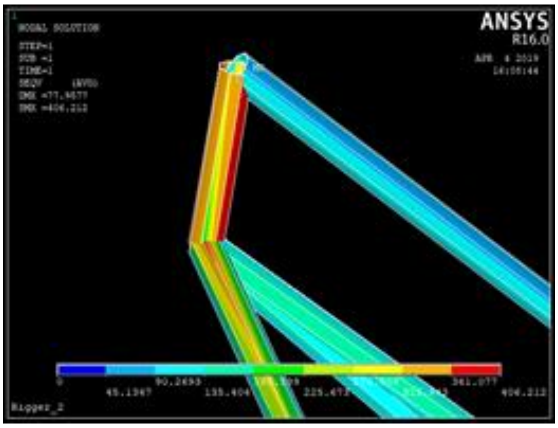


Fig 11: Von Mises Stress Max is 406.212 MPa Critical section is in Tholl pin axis (which is not the component of rigger and is made up of steel)

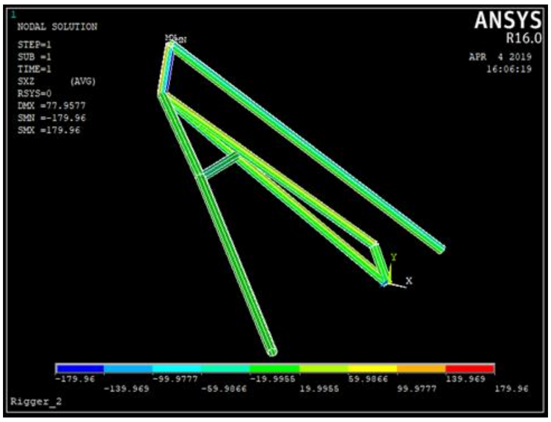


Fig 12 a : Shear Stress Max is 179.96 MPa

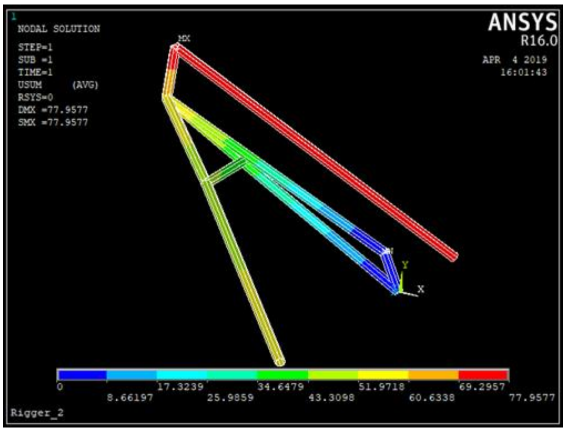


Fig 12 b: Displacement Sum is Max 77.96 mm

DISCUSSION

The FEM analysis gives us values of stresses induced in the rigger. These values are compared for permissible limits of material of rigger. Thus induced stresses are found to be within safe limits. This will help in further improvement in design and may also be helpful for the local manufacturers to have scientifically designed and tested rigger.

Though its sturdy rigger, the other issues faced by rowers using this kind of rigger are

These riggers are attached to the sides of the boat at lower level and hence get stuck in choppy water.

This increases resistance on the boat and thus reduces speed.

While parking the boat at jetty, this rigger dashes with the jetty.

CONCLUSION

The traditional tube rigger is modelled and analyzed in ANSYS. The FEM analysis demonstrated that the stress induced in tube rigger is within the permissible limits. The rigging system as a truss is simplified system for rowing force transfer from water to boat. Thus tube rigger is safe as per its current dimensions and the selected materials. The analysis well supports the Tholl pin design as solid bar of steel. This design can be adapted by local manufacturers of racing boat equipments.

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