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Natural Fibre Selection for Sustainable Two-stroke Marine Diesel Engine Crosshead Bearing

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Abstract: Two-stroke marine diesel engine components have primarily been made from steel. However, with ever increasing pressure from environmental policies, more sustainable alternative materials are currently being researched. The selection of the best natural fibre as potential material for a two-stroke marine diesel engine crosshead bearing was performed using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method. Eight different natural fibres were applied in ANSYS simulation to obtain the Maximum Stress (von Mises), Maximum Deformation and Weight of the crosshead bearing model. Using these three characteristics in the TOPSIS method, the best natural fibre material was found to be kenaf with a Relative closeness to ideal solution score of 0.955. Future work planned to further investigate the suitability of natural fibre as crosshead bearing material include studies on compressive stress, tribological behavior and effects of cyclic loading, relevant to conditions experienced in highly rated marine diesel engines.

Keywords: Two stroke marine diesel engine, TOPSIS, natural fibre composites

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1. Introduction

Two-stroke marine diesel engines provide the primary source of propulsion for over 90% of all cargo carrying vessels engaged in international trade [1]. The term “two-stroke engine” is often loosely used interchangeably with “crosshead engine” to describe the slow speed engines tasked with providing the power to propel various types of ships from bulk carriers to container ships to oil tankers. The crosshead assembly is a feature unique to these types of engines and provide the means of absorbing side thrust due to the connecting rod angularity while transferring the combustion force carried by the piston down to the connecting rod [2]. In operation, the crosshead goes through a back and forth “rocking” motion, where a hydrodynamically formed oil film separates the journal bearing from the crosshead pin. When at rest, the piston and piston rod assembly, hydraulically bolted to the pin rests squarely on the journal bearing. The bearings’ ability to withstand and support the weight of the components above it is of utmost importance at such a condition. It has been noted that at rest, any oil separating the pin and bearing tends to get squeezed out [3]. Visual details of the crosshead assembly making up part of the running gear in a two-stroke marine diesel engine is illustrated in Figure 1.

Journal bearings are presently manufactured from steel, which provides the necessary structure to the component. Tin-based white metal makes up a minute layer on top of the bearing surface meant to reduce friction and hold the lubricating oil during operation [5]. However, the processes involved in steel manufacturing has shown to be harmful to the environment as well as to human health [6], [7]. Steel production, in its various stages, require high consumptions of fossil fuel to power the large furnaces involved, which then contribute significantly to the emission of greenhouse gases into the environment. Additionally, the debris produced as a byproduct of steel manufacturing is a health hazard, particularly detrimental to the human respiratory system.

In light of ever-increasing pressure from environmental conservationists, the marine industry has made efforts as a whole to reduce the impact of global sea trade on the environment. Initiatives in the decarbonizing of ships, have driven various parties to search for the various ways that can further increase the ship’s fuel efficiency [8]. Some of the initiatives involved include research in ship design as well as studying the potential of using lighter materials in construction. Fuel efficiency is also improved when frictional resistance is reduced, whether across the ship's hull or specifically within the engine components. Substitution of bearing material from steel to natural fibre composites would provide a viable means of achieving reduced friction within the engine's running components.

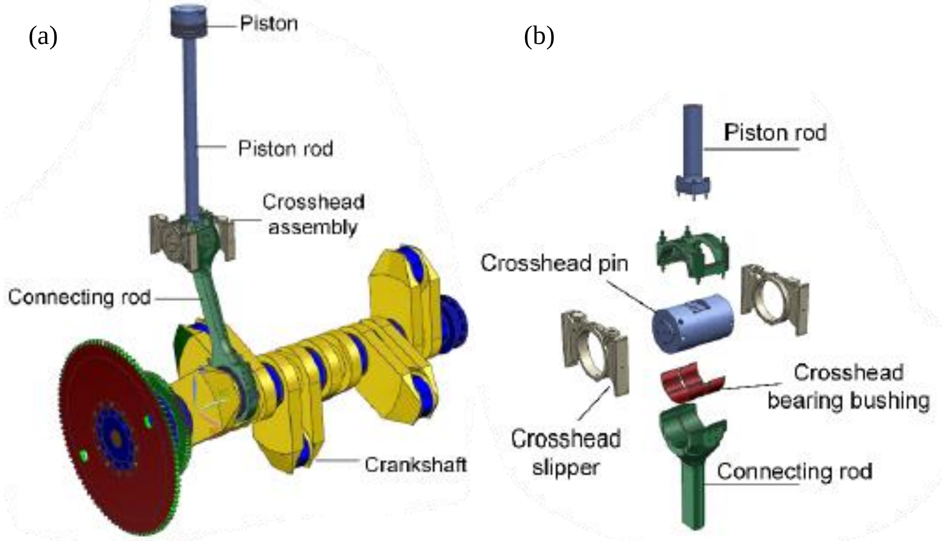

Figure 1: (a) Main running gear of a six cylinder two-stroke marine diesel engine showing the piston and crosshead assembly; (b) Exploded view of the crosshead assembly [4]

Natural fibre composites (NFC) have been widely researched in various sectors and applied in numerous applications across the world including those involving sea going vessel's hull structural members, propeller and shafting, and valves [9]; as well as those involving automotive parts ranging from parking hand brakes to side door impact beams to car hoods [10]–[12] NFC can be described as a composite of materials with elements of renewable natural fibres, mostly, of plant origin and of a carbon neutral source [13]. Natural fibres are naturally sourced and biodegradable, making it easier to dispose of at the end of its life cycle [14]. Industries involved in the application of NFC have long been attracted to the renewable and abundant aspect of natural fibres as well as the low density and cheaper cost. Chemical treatment of natural fibres have been reported to improve certain properties depending on the application in question [15]. For example, to increase boding between natural fibres and polymer matrix, isocyanate treatment would be beneficial, while treatment with alkaline tended to reduce the hydrophilic nature of natural fibres. The combination of natural fibres with polymer matrices in NFC improved wear resistance and friction compared to man-made fibres [16]. Although natural fibres vary in properties based on their species and place of harvest, arrangement of fibres play a role in influencing the strength of the composites [17].

The potential use of natural fibre as bearing material led to the ideation of a crosshead bearing design to accommodate the lower physical properties of natural fibres. This design was ideated using a hybrid of the Theory of Inventive Problem Solving (TRIZ) and biomimetics methods and is shown in Figure 2. The TRIZ is a design ideation method introduced to the world by Genrikh Saulovich Altshuller, a Russian scientist, after studying numerous patents [18], [19]. TRIZ provides generalized solutions based on the TRIZ Contradiction Matrix to help finding the ideal solution to the situation at hand. In brief, the TRIZ method requires the approach of identifying the feature/parameter that would need to be improved and the subsequent worsening or sacrifice of another. Upon identifying this pair of improving/worsening features, reference is made to the Contradiction Matrix to find recommended solutions to best solve the problem at hand. These solutions are often generalized but can often spark an idea in the psyche of the researchers involved. In various research, TRIZ has been shown to aid in problem solving involving human machine interface [20], promote idea generation in reciprocating seal improvement [21], as well as merge with other design ideation methods in other engineering endeavours [18], [22].

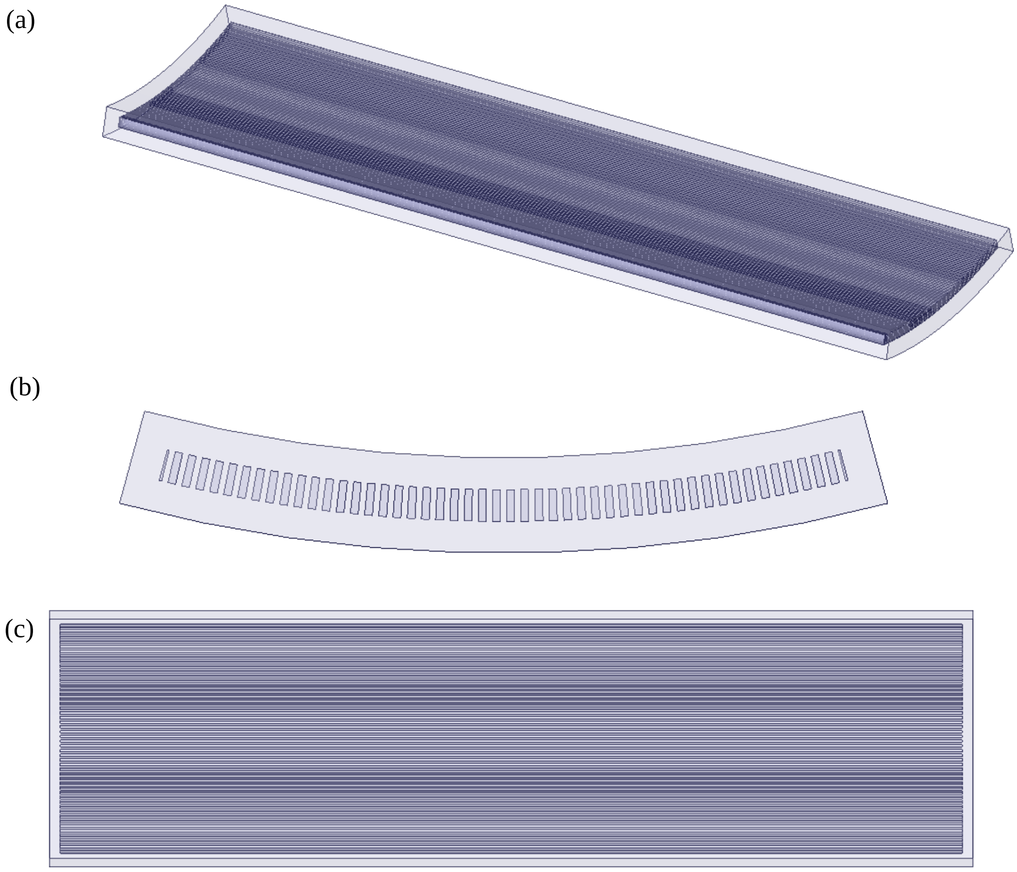

Figure 2: Design of bearing to accommodate natural fibre material shown in partial segment from (a) general view, (b) side elevation, (c) top view

Biomimetics takes notes from nature, and tries to replicate it to suit the solving of the problem faced in engineering [23]. By carefully observing the intricate workings of the natural world, answers can often be found for the solutions needed in designing and engineering problems in general. Where TRIZ offers generalized solutions, biomimetics analyses examples of specific applications in nature that may be applied to the problem at hand. It is through keen observation of nature that answer may be found. Among the engineering achievements of biomimetics are the Shinkansen bullet train nose cone inspired by the kingfisher's beak [23], [24], the Velcro strip inspired by burdock burrs [25], [26] and the Eastgate Centre in Zimbabwe inspired by termite mounds (Turner and Soar, 2008; French and Ahmed, 2010).

Synergy between the two ideation principles of TRIZ and biomimetics have been demonstrated in research, such as the conceptual design of a car side door impact beam [11], solving of contact failure in car electrical circuitry [27] and improvement of a valve cage resistance to erosion and impact (Cheng *et. al.*, 2019).

To the best of the authors knowledge, no work has been done involving the application of natural fibre material or NFC as material in marine diesel engine crosshead bearings. This work aims to introduce geometrical designs of journal bearings that can accommodate the use of natural fibre material as part of NFC as its main material.

2. Methodology

The process of determining the best natural fibre can be broken down into several steps as represented in Figure 3. The first step was to prepare the crosshead bearing model for simulation setup in ANSYS. This was then followed by the simulation of the crosshead bearing model to obtain data that will be used for the selection process. With the simulation results obtained, the selection of the best natural fibre was then performed using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method.

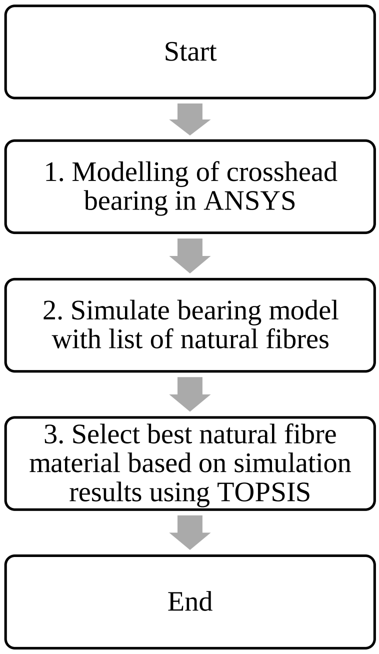

Figure 3: Natural fibre selection process flow

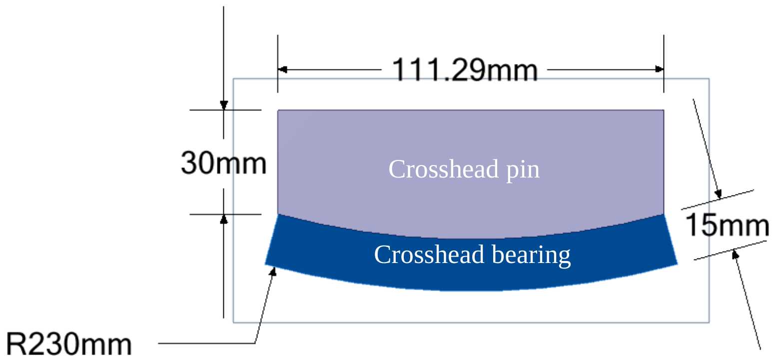

Figure 4: 2D setup of the model with dimensions

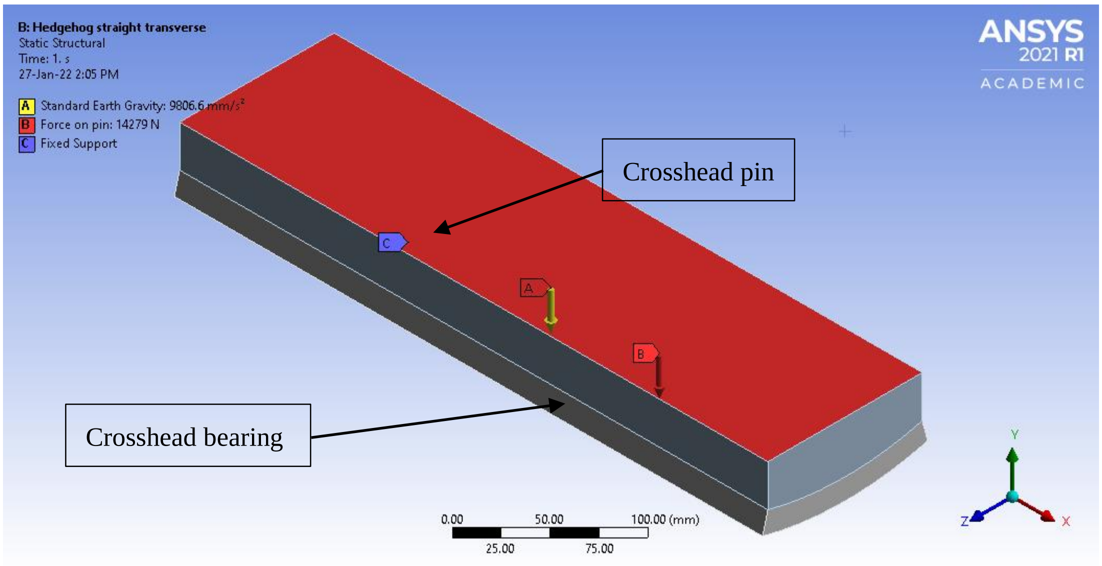

Figure 5: 3D drawing of the setup showing the partial crosshead pin and partial crosshead bearing

In the first step, modeling of the crosshead bearing was performed with ANSYS SpaceClaim for a 30° angle projection of the bearing. This was decided based on the study performed by Tachi et. al. (2005) where it was noted that the weight of the pin concentrated on a small section of the bearing directly below it [28]. So, to reduce computational time and load, only a partial section of the bearing was modelled for the simulation exercise. The completed model was then transferred to ANSYS Mechanical for setup of the simulation. A force of 14279.19 N was applied in the negative Y direction to represent the weight of the piston and piston rod assembly, which equates to 1469 kg [29]. The effect of gravity was set also in the negative Y direction with fixed support provided at the bottom of the bearing. The material of the pin was set to Structural steel and the bearing to natural fibre. Solution solver selections were made for obtaining Equivalent Stress (von Mises) and Total Deformation. Details of the setup are shown in Table 1. Figure 4 shows the 2D model with dimensions, while Figure 5 shows the 3D model setup of the partial crosshead pin and bearing assembly.

Table 1: Setup details for crosshead bearing simulation

Parameter
Pin material: Structural steel
Bearing material: natural fibre
Standard Earth Gravity: -Y direction
Fixed Support: Bottom of bearing
Force/Direction: -14279.188 N in the Y-direction
Solution solver: Equivalent Stress (von Mises) Total Deformation

The data for natural fibres necessary for the simulation were taken from Mastura et. al. (2017), specifically for density, Young's moduli and tensile strength and is listed in Table 2. These data were selected as they were required for the obtainment of maximum stress (von Mises), maximum deformation and weight, which would then be applied in the selection process. As the key aspect of the simulation was to determine the ability of the material to support the weight in a stationary position, the maximum stress (von Mises) gave the best indication of this. A high value would indicate that the material experienced a high value of stress and was more likely to fail. Maximum deformation provided key information on the materials' ability to hold the bearing shape. High values of this parameter represented a high amount of deformation, meaning a failure to maintain the bearing shape under the simulated load. The Weight of the material provided an indication of potential weight savings for the natural fibre when compared to conventional steel backed bearings.

With the simulated data, the next step involved the selection process. Given that the process involved is based on three criteria, the TOPSIS method was chosen. Developed by Hwang and Yoon in 1981, TOPSIS bases its selection on the hypothesis that the best option is nearest to the Positive Ideal Solution (PIS) and farthest from the Negative Ideal Solution (NIS) [30]. The decision to use TOPSIS in the selection process was due to this method being particularly well documented in decision making across various disciplines [31].

Table 2: Properties of natural fibres [32]

Properties	Unit	Sugar Palm	Kenaf	Oil Palm	Sisal	Jute	Hemp	Flax	Pineapple	Coir
Density	g/cm^3	1.24	1.3	1.125	1.5	1.3	1.48	1.5	1.2	1.2
Young's Modulus	GPa	5.9	53	3.2	15.7	26.5	70	27.6	1.44	5
Tensile Strength	MPa	276.6	930	248	573	583	690	690	513.5	175

The TOPSIS method is explained in the following steps:

Step One: formulate the TOPSIS decision matrix.

$$D = \begin{vmatrix} & C_1 & C_2 & \dots & C_n \\ A_1 & X_{11} & X_{12} & \dots & X_{1n} \\ A_2 & X_{21} & X_{22} & \dots & X_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_m & X_{m1} & X_{m2} & \dots & X_{mn} \end{vmatrix} \quad (1)$$

where:

$A_1, A_2, \dots, A_m$ are potential alternatives that the decision maker has to select;

$C_1, C_2, \dots, C_n$ are the criterion from which the potential alternative performances are measured;

X_{ij} is the rating of alternative A_i with reference to criterion C_j where w_j is the weightage assigned to criterion C_j and $w_1 + w_2 + \dots + w_n = 1$ [33].

Step Two: calculate the normalised matrix, n_{ij}:

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad (2)$$

where $i = 1, 2, \dots, m; j = 1, 2, \dots, n$.

Step Three: calculate the weighted normalised decision matrix, v_{ij}:

$$v_{ij} = w_j n_{ij} \quad (3)$$

where:

$i = 1, 2, \dots, m; j = 1, 2, \dots, n$.

w_j is the weight of the jth criterion, and $\sum_{j=1}^{n} w_j = 1$.

Step Four: determine the ideal best and ideal worst values:

$$A^+ = \{v_1^+, v_2^+ \dots, v_n^+\} = \left\{ \left(\max_i v_{ij} \mid \ j \in I \right), \left(\min_i v_{ij} \mid \ j \in J \right) \right\} \quad (4)$$

$$A^- = \{v_1^-, v_2^- \dots, v_n^-\} = \left\{ \left(\min_i v_{ij} \mid \ j \in I \right), \left(\max_i v_{ij} \mid \ j \in J \right) \right\} \quad (5)$$

where I is associated with the beneficial criterion and J is associated with the cost criterion.

Step Five: calculate the separation measures, using the n-dimension Euclidian distance. For each alternative, the distance is defined as:

$$d_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_i^+ \right)^2} \quad (6)$$

where $i = 1, 2, \dots, m$.

$$d_j^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_i^- \right)^2} \quad (7)$$

where $i = 1, 2, \dots, m$.

Step Six: calculate the relative closeness to the ideal solution. The relative closeness of the alternative A_j with respect to A^+ is defined:

$$R_i = \frac{d_j^-}{\left(d_j^- + d_j^+ \right)} \quad (8)$$

where $0 \le R_i \le 1$, $i = 1, 2, \dots, m$.

Step Seven: rank the preference order in descending value of R_i.

3. Results and Discussion

Previous research performed for material selection involved using the material data as the criteria for multiple criteria decision making methods [34]–[36]. However, in the opinion of the authors, the selection of material for the crosshead bearing warrants the use of the simulation data. This provides a more accurate representation of the capabilities of the natural fibre in performing the intended duty of a crosshead bearing. The values obtained for maximum stress (von Mises), maximum deformation and Weight provide clearer meaning to the evaluation compared to the values of Young's modulus, tensile strength and density. As such, it is in the opinion of the authors that the simulation results take precedence in the selection process.

The results for maximum stress (von Mises), maximum deformation and weight from the simulation exercise are shown in Table 3 for the list of natural fibre materials as well as Structural Steel (SS) for comparison. Based on the results obtained, the natural fibre with the lowest maximum stress (von Mises) is Oil Palm. In comparison to SS, all the natural fibres simulated registered lower maximum stress (von Mises) readings. The lowest maximum deformation was for Hemp at 1.41×10^{-4} mm, which is however, higher than that of SS. Where weight is concerned, the lowest valued natural fibre was for Oil Palm at 0.700 kg, significantly lower than SS at 4.882 kg.

Table 3: Simulation results for natural fibre material in comparison to structural steel

	Maximum Stress (Von Mises) (MPa)	Maximum Deformation (mm)	Weight (kg)
Structural Steel	0.700	9.38E-05	4.882
Coir	0.633	1.06E-03	0.746
Pineapple	0.635	3.53E-03	0.746
Flax	0.644	2.46E-04	0.933
Hemp	0.677	1.41E-04	0.920
Jute	0.643	2.54E-04	0.809
Sisal	0.637	3.78E-04	0.933
Oil Palm	0.632	1.62E-03	0.700
Kenaf	0.667	1.63E-04	0.809
Sugar Palm	0.633	9.03E-04	0.771

The determination of the best natural fibre required the selection to be performed from an overall analysis of the results rather than just emphasizing individual characteristics. In order to obtain a clear selection of the best natural fibre using the TOPSIS method, weightage was first decided for the three criteria. The weightage selected for these criteria were based on the author's experience while serving on crude oil tankers propelled by two-stroke marine diesel engines. The determined weightage is presented in Table 4. The subsequent steps in TOPSIS as defined in Equations (1) to (8) are tabulated in Tables 5 to 8 below.

Table 4: Weightage determined for each criterion

	Maximum Stress (Von Mises) (MPa)	Maximum Deformation (mm)	Weight (kg)
Weightage	0.4	0.35	0.25

Table 5: Normalized matrix

	Maximum Stress (Von Mises) (MPa)	Maximum Deformation (mm)	Weight (kg)
Coir	0.327	0.302	0.253
Pineapple	0.328	0.302	0.848

Flax	0.333	0.378	0.059
Hemp	0.350	0.373	0.034
Jute	0.332	0.328	0.061
Sisal	0.329	0.378	0.091
Oil Palm	0.327	0.283	0.389
Kenaf	0.345	0.328	0.039
Sugar Palm	0.327	0.312	0.217

Table 6: Weighted normalized matrix

	Maximum Stress (Von Mises) (MPa)	Maximum Deformation (mm)	Weight (kg)
Coir	0.131	0.076	0.089
Pineapple	0.131	0.076	0.297
Flax	0.133	0.094	0.021
Hemp	0.140	0.093	0.012
Jute	0.133	0.082	0.021
Sisal	0.132	0.094	0.032
Oil Palm	0.131	0.071	0.136
Kenaf	0.138	0.082	0.014
Sugar Palm	0.131	0.078	0.076

Table 7: Positive and negative ideal solution matrix

	Maximum Stress (Von Mises) (MPa)	Maximum Deformation (mm)	Weight (kg)
Positive ideal solution	0.131	0.012	0.071
Negative ideal solution	0.140	0.297	0.094

Table 8: Overall ranking for natural fibre material selection

	Positive ideal solution	Negative ideal solution	Relative closeness to the ideal solution	Rank
Coir	0.077	0.209	0.731	7
Pineapple	0.285	0.021	0.068	9
Flax	0.025	0.276	0.916	4
Hemp	0.024	0.285	0.922	3
Jute	0.015	0.276	0.949	2
Sisal	0.031	0.265	0.896	5
Oil Palm	0.124	0.163	0.568	8
Kenaf	0.013	0.283	0.955	1
Sugar Palm	0.064	0.222	0.775	6

The final results of the TOPSIS method for selection are shown in Table 8. Based on the results, kenaf is concluded to be the best natural fibre material with a Relative closeness to the ideal solution value of 0.955. This is followed by jute (0.949), hemp (0.922), flax (0.916), sisal (0.896), sugar palm (0.775), coir (0.731), oil palm (0.568) and pineapple (0.068), respectively. When the simulation from Table 2 is scrutinized, it can be seen that kenaf did register the second highest maximum stress (von Mises) at 0.667 MPa, only lower compared to hemp (0.677 MPa). However, the maximum deformation experienced by kenaf fibre in the bearing model was among the lowest at 1.63×10^{-4} mm, second only to hemp at 1.41×10^{-4} mm. This indicates that kenaf has a reasonably good ability to hold the bearings' shape under the static load, which is critical in other functions of the bearing such as the ability to support lubricating oil and aid in development of hydrodynamic lubrication during operation [5]. The weight of the bearing with kenaf scored a value of 0.809 kg, which is tied for fourth/fifth place among all the simulated natural fibre materials.

4. Conclusions

The results obtained from the analysis of simulation data showed the potential of natural fibre material as substitute for Structural steel in crosshead bearings. In terms of Maximum deformation and maximum stress (Von Mises), the results have shown comparability between Structural steel and natural fibre material, specifically kenaf and jute. Although somewhat comparable, it should be reminded that these were obtained through computer simulation and would need to be verified through experimental means. Regardless, these results give reason for further studies to be conducted into natural fibre as a viable sustainable alternative in engine component manufacturing with low environmental impact. This research may have been focused on the heavily loaded crosshead bearing, but the results are applicable to other related machinery found in the ship's engine room, such as centrifugal oil purifiers, reciprocating compressors and pumps as well.

Future work planned to provide better understanding of suitability of natural fibre material as crosshead bearings include studies on:

i. The compressive strength of natural fibre materials, given the way that crosshead bearings are loaded, which generates compressive stresses in the bearing material.

ii. The behavior of natural fibre materials when subjected to cyclic loading similar to that experienced by the crosshead bearing assembly, consisting of an alternate between a downward load brought about by firing forces and weight of the piston assembly and an upward reversal carried by the rotation of the crankshaft.

iii. The tribological behavior of natural fibre materials, particularly in hydrodynamic and hydrostatic conditions, considering the revolute joint nature of the crosshead assembly.

iv. The mechanical characteristics of natural fibre materials when combined with polymer matrices, similar to those found in NFC.

References

[1] R. E. J. Schnurr and T. R. Walker, "Marine Transportation and Energy Use," *Ref. Modul. Earth Syst. Environ. Sci.*, no. October, 2019, doi: 10.1016/b978-0-12-409548-9.09270-8.

[2] M. Latarche, *Introduction*, 10th ed. Oxford: Elsevier Ltd., 2021.

[3] I. Hutchings and P. Shipway, "Applications and case studies," in *Tribology: friction and wear of engineering materials*, Oxford: Butterworth-Heinemann, 2017, pp. 303–352.

[4] R. Li, X. Meng, J. Dong, and W. Li, "Transient tribo-dynamic analysis of crosshead slipper in low-speed marine diesel engines during engine startup," *Friction*, vol. 9, no. 6, pp. 1504–1527, 2021, doi: 10.1007/s40544-020-0433-9.

[5] C. H. Simmons, D. E. Maguire, and N. Phelps, "Bearings and applied technology," in *Manual of Engineering Drawing (Fifth Edition)*, 2020, pp. 519–545.

[6] G. M. Olmez, F. B. Dilek, T. Karanfil, and U. Yetis, "The environmental impacts of iron and steel industry: A life cycle assessment study," *J. Clean. Prod.*, vol. 130, pp. 195–201, 2016, doi: 10.1016/j.jclepro.2015.09.139.

[7] D. Burchart-Korol, "Life cycle assessment of steel production in Poland: A case study," *J. Clean. Prod.*, vol. 54, pp. 235–243, 2013, doi: 10.1016/j.jclepro.2013.04.031.

[8] G. Mallouppas and E. A. Yfantis, "Decarbonization in Shipping industry: A review of research, technology development, and innovation proposals," *J. Mar. Sci. Eng.*, vol. 9, no. 4, 2021, doi: 10.3390/jmse9040415.

[9] A. P. Mouritz, E. Gellert, P. Burchill, and K. Challis, "Review of advanced composite structures for naval ships and

submarines," *Compos. Struct.*, vol. 53, no. 1, pp. 21–42, 2001, doi: 10.1016/S0263-8223(00)00175-6.

[10] M. R. Mansor, S. M. Sapuan, E. S. Zainudin, A. A. Nuraini, and A. Hambali, "Conceptual design of kenaf fiber polymer composite automotive parking brake lever using integrated TRIZ-Morphological Chart-Analytic Hierarchy Process method," *Mater. Des.*, vol. 54, pp. 473–482, 2014, doi: 10.1016/j.matdes.2013.08.064.

[11] M. A. Shaharuzaman, S. M. Sapuan, M. R. Mansor, and M. Y. M. Zuhri, "Conceptual design of natural fiber composites as a side-door impact beam using hybrid approach," *J. Renew. Mater.*, vol. 8, no. 5, pp. 549–563, 2020, doi: 10.32604/jrm.2020.08769.

[12] N. M. Ishak, S. D. Malingam, and M. R. Mansor, "Selection of natural fibre reinforced composites using fuzzy VIKOR for car front hood," *Int. J. Mater. Prod. Technol.*, vol. 53, no. 3–4, pp. 267–285, 2016, doi: 10.1504/IJMPT.2016.079205.

[13] Y. K. Kim, "Natural fibre composites (NFCs) for construction and automotive industries," in *Handbook of Natural Fibres*, no. 2000, Woodhead Publishing Limited, 2012, pp. 254–279.

[14] P. Balakrishnan, M. J. John, L. Pothen, M. S. Sreekala, and S. Thomas, *Natural fibre and polymer matrix composites and their applications in aerospace engineering*. Elsevier Ltd, 2016.

[15] A. Dasore, U. Rajak, R. Balijepalli, T. N. Verma, and K. Ramakrishna, "An overview of refinements, processing methods and properties of natural fiber composites," *Mater. Today Proc.*, 2021, doi: 10.1016/j.matpr.2021.02.103.

[16] E. Omrani, P. L. Menezes, and P. K. Rohatgi, "State of the art on tribological behavior of polymer matrix composites reinforced with natural fibers in the green materials world," *Eng. Sci. Technol. an Int. J.*, vol. 19, no. 2, pp. 717–736, 2016, doi: 10.1016/j.jestch.2015.10.007.

[17] S. Ravindran, G. G. Sozhamannan, L. Saravanan, and V. S. K. Venkatachalapathy, "Study on mechanical behaviour of natural fiber reinforced vinylester hybrid composites," *Mater. Today Proc.*, vol. 45, 2021, doi: 10.1016/j.matpr.2020.12.1077.

[18] C. Lim, D. Yun, I. Park, and B. Yoon, "A systematic approach for new technology development by using a biomimicry-based TRIZ contradiction matrix," *Creat. Innov. Manag.*, vol. 27, no. 4, pp. 414–430, 2018, doi: 10.1111/caim.12273.

[19] P. R. N. Childs, "Ideation," in *Mechanical Design Engineering Handbook*, 2nd ed., 2019, pp. 75–144.

[20] D. A. Coelho, "Matching TRIZ engineering parameters to human factors issues in manufacturing," *WSEAS Trans. Bus. Econ.*, vol. 6, no. 11, pp. 547–556, 2009.

[21] F. Y. Zhang, T. Li, and H. C. Zhang, "Study on the efficiency-reinforcement design for elastomeric hydraulic reciprocating sealing based on QFD/TRIZ," *Mater. Sci. Forum*, vol. 770, pp. 312–315, 2014, doi: 10.4028/www.scientific.net/MSF.770.312.

[22] M. R. Mansor, S. M. Sapuan, A. Hambali, E. S. Zainudin, and A. A. Nuraini, "Conceptual Design of Kenaf Polymer Composites Automotive Spoiler Using TRIZ and Morphology Chart Methods," *Appl. Mech. Mater.*, vol. 761, pp. 63–67, 2015, doi: 10.4028/www.scientific.net/amm.761.63.

[23] P. E. Fayemi, N. Maranzana, A. Aoussat, and G. Bersano, "Bio-inspired design characterisation and its links with problem solving tools," *Proc. Int. Des. Conf. Des.*, pp. 173–182, 2014.

[24] C. Hood, *Shinkansen From Buller Train to Symbol of Modern Japan*, 1st ed., vol. 1. London: Routledge, 2006.

[25] T. Stephens, "How a Swiss invention hooked the world," *Swiss info.ch*, 2007. http://www.swissinfo.ch/eng/archive/How_a_Swiss_invention_hooked_the_world.html?cid=5653568.

[26] B. Bhushan, "Biomimetics: Lessons from Nature - an overview," *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, vol. 367, no. 1893, pp. 1445–1486, 2009, doi: 10.1098/rsta.2009.0011.

[27] T. W. Liskiewicz, K. J. Kubiak, D. L. Mann, and T. G. Mathia, "Analysis of surface roughness morphology with TRIZ methodology in automotive electrical contacts: Design against third body fretting-corrosion," *Tribol. Int.*, vol. 143, no. August 2019, 2020, doi: 10.1016/j.triboint.2019.106019.

[28] Y. Tachi, S. Ishihara, K. Tamura, T. Goshima, and A. J. McEvily, "Predicting sliding wear behaviour of a tin-based white metal under varying pressure and speed conditions," *Proc. Inst. Mech. Eng. Part J J. Eng. Tribol.*, vol. 219, no. 6, pp. 451–457, 2005, doi: 10.1243/135065005X34035.

[29] "Volume II: Maintenance," in *Electronic Instruction Manual for Engine Type: 6S60MC*, Kyungnam: HSD Engine Co., Ltd., 2003, p. Data 1(1).

[30] C.-L. Hwang and K. Yoon, "Multiple Attributes Decision Making Methods and Applications," *Mult. Attrib. Decis. Mak.*, pp. 58–191, 1981.

[31] E. K. Zavadskas, A. Mardani, Z. Turskis, A. Jusoh, and K. M. Nor, "Development of TOPSIS Method to Solve Complicated Decision-Making Problems: An Overview on Developments from 2000 to 2015," *Int. J. Inf. Technol. Decis. Mak.*, vol. 15, no. 3, pp. 645–682, 2016, doi: 10.1142/S0219622016300019.

[32] M. T. Mastura, S. M. Sapuan, M. R. Mansor, and A. A. Nuraini, "Environmentally conscious hybrid bio-composite material selection for automotive anti-roll bar," *Int. J. Adv. Manuf. Technol.*, vol. 89, no. 5–8, pp. 2203–2219, 2017, doi: 10.1007/s00170-016-9217-9.

[33] E. Roszkowska, "Multi-Criteria Decision Making Models By Applying the TOPSIS Method To Crisp and Interval Data," *Int. Sci. J.*, vol. 6, no. 1, pp. 200–230, 2011.

[34] M. T. Mastura, S. M. Sapuan, M. R. Mansor, and A. A. Nuraini, "Materials selection of thermoplastic matrices for 'green' natural fibre composites for automotive anti-roll bar with particular emphasis on the environment," *Int. J. Precis. Eng. Manuf. - Green Technol.*, vol. 5, no. 1, pp. 111–119, 2018, doi: 10.1007/s40684-018-0012-y.

[35] M. A. Shaharuzaman, S. M. Sapuan, M. R. Mansor, and M. Y. M. Zuhri, "Decision support strategy in selecting natural fiber materials for automotive side-door impact beam composites," *J. Renew. Mater.*, vol. 7, no. 10, pp. 997–1010, 2019, doi: 10.32604/jrm.2019.07529.

[36] M. R. Mansor, S. M. Sapuan, A. Hambali, E. S. Zainudin, and A. A. Nuraini, "Materials selection of hybrid bio-composites thermoset matrix for automotive bumper beam applicationusing TOPSIS method," *Adv. Environ. Biol.*, vol. 8, no. 8 SPEC. ISSUE 3, pp. 3138–3142, 2014.

[37] R. A. Ilyas, S. M. Sapuan, and M. R. Ishak, "Isolation and characterization of nanocrystalline cellulose from sugar palm fibres (Arenga Pinnata)," *Carbohydr. Polym.*, vol. 181, pp. 1038–1051, Feb. 2018, doi: 10.1016/j.carbpol.2017.11.045.

[38] M. M. Harussani, S. M. Sapuan, U. Rashid, A. Khalina, and R. A. Ilyas, "Pyrolysis of polypropylene plastic waste into carbonaceous char: Priority of plastic waste management amidst COVID-19 pandemic," *Sci. Total Environ.*, vol. 803, p. 149911, Jan. 2022, doi: 10.1016/j.scitotenv.2021.149911.

[39] M. R. M. Asyraf *et al.*, "Potential application of green composites for cross arm component in transmission tower: A brief review," *Int. J. Polym. Sci.*, vol. 2020, 2020, doi: 10.1155/2020/8878300.