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The Importance of Geometrical Parameters on the Mechanical Stability of Roebel Cables

Gijoy. S and K E. Reby Roy

***Abstract*—AC loss from Roebel cables with High-Temperature Superconducting (HTS) strands are comparatively less, and they possess large current carrying capacity since they have a transposed structure. However, the strands should be strong enough to withstand various types of external loads during their operation. The present work simulates the performance of the Roebel strand against an external tensile load using 3D finite element analysis (FEA), and the importance of geometrical parameters on the mechanical stability of Roebel cables is investigated. Results were then compared with another work where the analyses were performed on a monolithic Roebel strand. We concluded that the typical twisting of the strands is an important parameter that cannot be ignored when optimizing a Roebel cable. Hence, the stress induced in a Roebel strand against an external load depends not only on the geometrical parameters but also on the typical twisting of the strand.**

***Index Terms*—Finite element analysis, geometry, relative von-Mises stress, Roebel cable, twisting.**

I. Introduction

HIGHER current densities are required for the smooth operation of accelerators, superconducting magnets, large transformers and similar high power electrical machines. High-Temperature Superconducting (HTS) cables can develop this high-intensity current in the range of kA/mm^2 without much losses [1] [2]. Among the cable configurations that incorporated HTS as thin layers, the meander shaped Roebel geometry shows high current density and low AC losses [3]. Roebel cables possess a transposed structure, which goes towards reducing the current imbalance among strands [4].

HTS conductors, including Roebel cables, are subjected to twisting, bending, compression, tension during their application. The combined effect of all the circumstances mentioned above may also occur, therefore the cables must be strong enough to withstand such loads. Sliding can also occur between the strands of a Roebel cable [4]. The punched out section of the Roebel strands are the prime area of stress concentration under external loading [5]. The shape of this section depends on the geometrical parameters, and the variation of its dimension varies the magnitude of stress developed. Hence, the influence of these effects on the mechanical stability of Roebel cables must be investigated and appropriately tested before proceeding into the application field.

As the potential of HTS in various applications is increasing, it is essential to do 3D finite element analysis (FEA) that can simulate the real-world physical problems of the HTS Roebel cables which favors the design and fabrication of effective cables. Some authors performed the FEA of Roebel cables using 3D simulation technique, however, each one has its constraints. In the work [5], the resistance of Roebel cables with various geometrical parameters against the external tensile load was performed using 3D finite-element-method (FEM). They considered the HTS tape as monolithic and straight. They reported that the mechanical strength of the Roebel cable is strongly influenced by the parameters like the inner radius, outer radius, Roebel angle and the relative width of the strand. However, they overlooked the importance of transposition length, the number of strands and the typical twisting of the strand. The Roebel strand in its bound state (cable) is not straight; instead, a small twist occurs due to the overlapping of each strands. The present work simulates the performance of such a distorted Roebel strand against an externally applied tensile load using 3D finite element analysis (FEA). Also, the influence of geometrical parameters such as Roebel angle, inner radius, outer radius and the relative width of the Roebel strand is investigated. The obtained outcomes were then compared with [5] to analyze the effect of considering strand's natural twist.

II. Model description

Coated conductor tapes are typically used for the production of Roebel cables. The most accepted method is the design used by Industrial Research Limited (IRL) [6]. The mechanical punching method developed by the Karlsruhe Institute of Technology (KIT) and IRL is typically used for the production of meander shaped Roebel strands [7]. The design of an yttrium barium copper oxide (YBCO) coated conductor tape, developed by SuperPower Inc. [8] is represented in Fig. 1.

This paragraph of the first footnote will contain the date on which you submitted your paper for review. It will also contain support information, including sponsor and financial support acknowledgment. For example, "This work was supported in part by the U.S. Department of Commerce under Grant BS123456."

Gijoy. S and K E. Reby Roy is with Department of Mechanical Engineering, Thangal Kunju Musaliar College of Engineering, Karikode, Kollam - 691005, Kerala, India. (e-mail: gijoys@sctce.ac.in; rebyroy@tkmce.ac.in).

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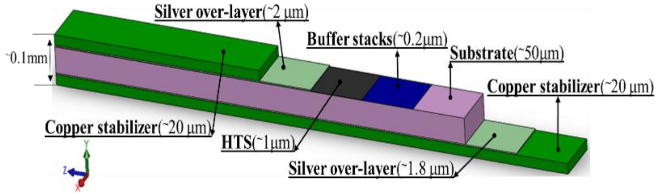

Fig. 1. The structure of 2G HTS tape developed by SuperPower Inc. [8].

In the present work, the 3D meander shape of both straight and twisted Roebel strands were modelled using the CAD software SOLIDWORKS 2014. The specification of the straight Roebel strand for modelling, validation and analysis were taken from the dimensions mentioned in [5] and [9]. However, the twisted strands were modelled by considering the number of strands in the Roebel cable as 14. The specification of the Roebel cable considered for simulation is mentioned in Table I.

TABLE I
SPECIFICATION OF THE ROEBEL CABLE CONSIDERED FOR SIMULATION

Symbol	Parameters	Value
W_t	Width of the tape	4 mm
W_R	Strand width of straight section	2 mm
W_x	Strand width at transposition section	2 mm
φ	Roebel angle	30°
L	Transposition length (cabling pitch)	109 mm
N	Number of strands	14
t	Total thickness of Roebel strand	0.1 mm

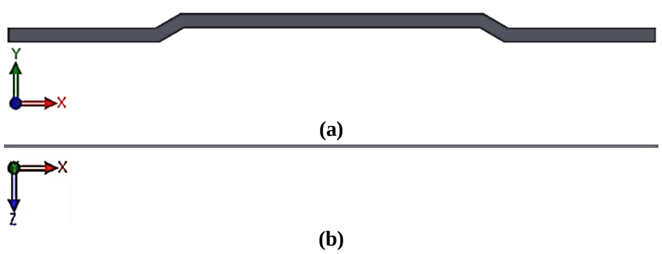

Fig. 2. Sketch of a Roebel strand shown in two different orientations. (a) Front view of the Roebel strand (b) Top view of the Roebel strand. The figure shows only one transposition length.

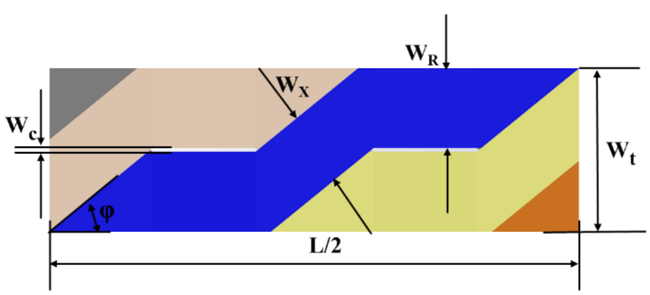

Fig. 3. 2D illustration of the cross-over region of a Roebel cable.

The geometry of the straight Roebel strands were modelled first. The strands were then imported into the assembling platform available within the CAD modelling software. As the strands were straight, assembling them into cable causes the strands to overlap at several position along the cable longitudinal direction. The position and area at which overlapping between strands occurs is identified and suitable modifications were made on the model of straight strand to obtain twisted strands. The twisted strands thus created were then imported to the assembling platform to create the 14-strand Roebel cable. Fig. 2 represents the two different orientations of an individual straight Roebel strand. The parameters and the 2D representation of a portion of the Roebel cable are represented in Fig. 3.

The production of Roebel cables creates a natural twist on all strands due to the transposition of each strand [9]. We noted that the normal twisting of the Roebel strand depends on the following parameters: the width of the tape (W_t), strand width of the straight section (W_R), strand width of the transposition section (W_x), the gap between stacks of strands in the straight section (W_c), transposition length (cabling pitch) (L), Roebel angle (φ), the number of strands (N), the total thickness of Roebel strand (t) [10].

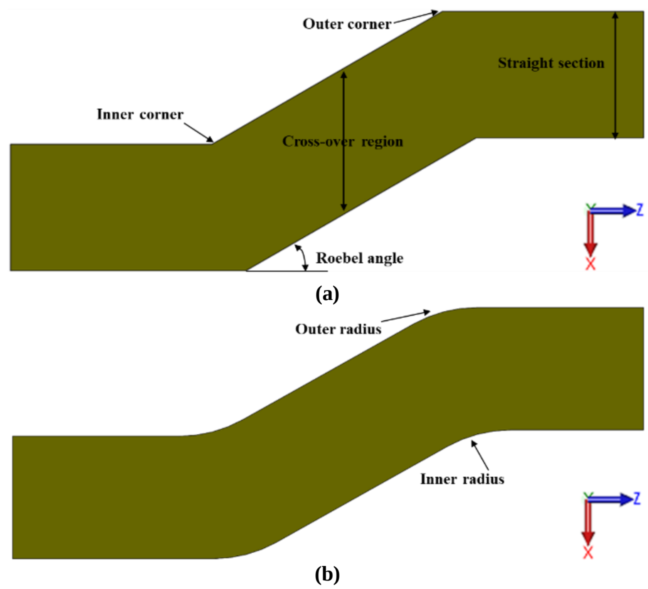

Fig. 4. The cross-over region of a Roebel strand. (a) Strand with sharp corners (b) strand with radial fillet.

The structure of a Roebel strand consists of the crossing section, straight section, outer corner, inner corner, Roebel angle, inner radius, outer radius, etc. All these areas are marked in Fig. 4. If the contact between the straight portion and the cross-over region becomes sharp, then it is called an inner corner/outer corner. If a fillet is given at this region, then it is called an inner radius/outer radius. The orientation of the strand determines the inner and outer region.

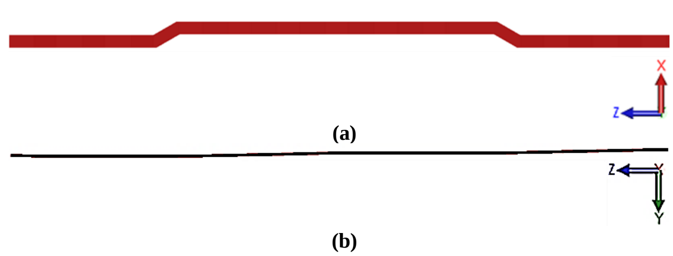

Fig. 5. Two different orientations of a Roebel strand removed from a 14-strand cable. (a) Front view of the Roebel strand (b) Top view of the Roebel strand. The figure shows only one transposition length.

Fig. 5 shows a Roebel strand separated from a 14-strand

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cable. The top view of the figure indicates the normal twisting happens on the strand during its winding into the required cable configuration. The 3D modelling of the Roebel cable was completed by keeping all cross-over surface of the strands in the same plane.

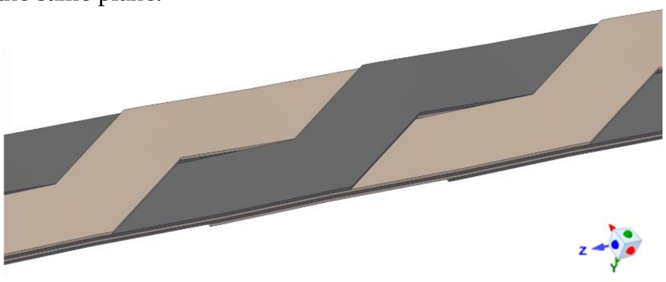

Fig. 6. 3D representation of the transposition region of a Roebel cable.

Fig. 6 displays the overlapping of five strands of a Roebel cable. From the figure, we can ensured the alignment, position, and overlapping of strands, i.e. the meander shape of the Roebel cable. Also, the strand in the cable was not straight, but has a slight twist in the area where the next strand is transposed. Moreover, the position at which this twisting occurs depended on parameters like the width of the tape, the width of strand at the straight section, strand width at the transposition section, the gap between stacks of strands in the straight section, transposition length, Roebel angle, the number of strand in a cable, the total thickness of Roebel strand. For example, in a 14-strand cable of 109 mm transposition length, the longitudinal distance between outer corners of two consecutive strands was approximately 7.78 mm. This distance was different for a 14-strand cable of 90 mm transposition length. Hence, the transposition length influenced the point about which the twisting of the strand occurs. If we changed the Roebel angle instead of the transposition length, then it affected the position of the cross over section, which in turn affected the position about which twisting of the strand occurs. Similarly, changes in the dimension of any parameter influenced the position and degree of twisting of the Roebel strand if we keep the alignment of surfaces of the cross over section in the same plane.

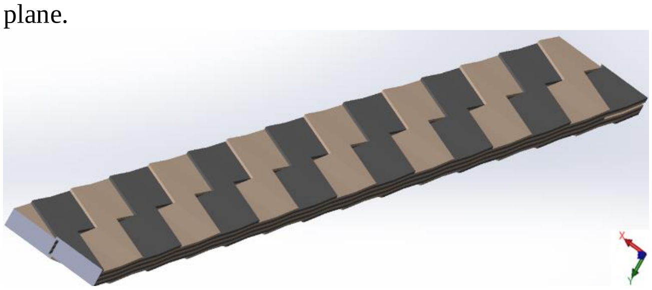

Fig. 7. The 3D view of a 14-strand Roebel cable. A length of one transposition is cut-out from the assembled cable configuration.

The assembled view of a 14-strand Roebel cable is illustrated in the Fig. 7. The figure gives a clear indication that all strands in the cable have a natural twist. Such distortions develop in the area where one strand crosses the other [11]. To the best of our knowledge, all the previous mechanical simulations and analyses overlooked the natural twisting of the strand in its FE model.

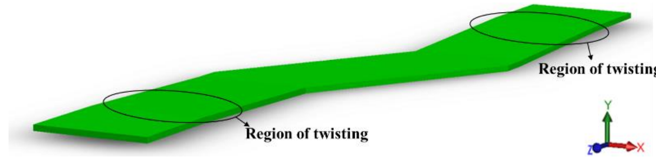

Fig. 8. The cross-over region of a Roebel strand with normal twisting.

To achieve a consistent and similar result; the same assumptions, terms, property values, boundary conditions and the region took for analysis of [5] were also considered in the present work. The area where strands are transposed was taken into consideration for study as this section of the strand has sharp inner and outer corners. The geometrical parameters considered to be varied during the simulation of present work is marked in Fig. 4. The same portion of a twisted Roebel strand is also shown in Fig. 8. Another parameter that varied in the present work was the relative width, which is the ratio of the width of the crossing section to the width of the straight section. The range up to which each parameter was varied in the simulation is shown in Table II.

TABLE II
RANGE OF EACH PARAMETERS CONSIDERED IN SIMULATION

Parameters	Range
Outer fillet	0 to 6 mm
Inner fillet	0 to 12 mm
Roebel angle	20^{o} to 50^{o}
Relative width	0.75 to 1.5

III. FINITE ELEMENT ANALYSIS AND SIMULATION METHOD

The finite element analysis of the 3D model (both straight and twisted) was performed using Ansys 14.5. In the present work, a 4 mm wide HTS tape was used to model the Roebel strand. For validation, the mechanical analysis done in [5] of a monolithic strand with parameters outer corner and inner fillet radius changing from zero to 12 mm was simulated, and the results were compared. It showed an acceptable range.

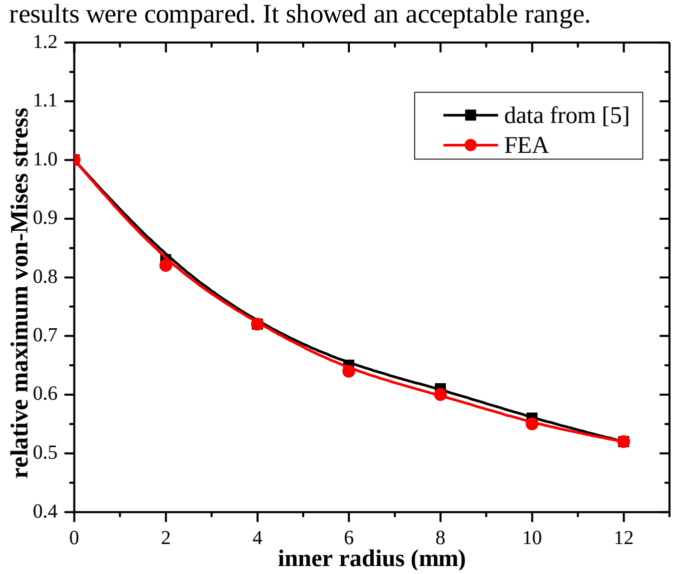

Fig. 9. Graph showing the comparison between FEA and the data from [5]. A monolithic strand of outer corner sharp and inner radius changing is considered for the comparison.

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Even though the HTS Roebel strand consists of many layers; for simplifying the geometrical model and reducing the computational effort, all the other sublayers were neglected, and the strand was considered as a single material of thickness 0.1 mm, and the mechanical properties were assumed equal to the weighted average ratio of all layers in the HTS strand. The Poisson ratio of the strand was assumed as 0.311, and the Young's modulus was taken as 120 GPa. Property values corresponding to 77 K was considered for simulation [5]. One end of the strand was given fixed support, and to the other end, a force of 1000 N was applied gradually. To the straight section and on the side face of the tape, frictionless roller supports were given. The above constraints only allowed the strand to move in the direction of the applied tensile load. Hence, the deformation occurred in that direction only. Mesh convergence tests were performed to confirm that adequate finite element mesh resolutions were used. The material properties and boundary conditions mentioned here were taken precisely the same as that illustrated in [5] for getting a comparable result. The only difference between the present work and the condition mentioned in [5] is that in [5] the tape was considered as monolithic; in the present work, the strand's natural twisting is also considered. From the simulation, the relative maximum von-Mises stress was calculated and compared with the results reported in [5]. Relative maximum von-Mises stress means the ratio of maximum von-Mises stress obtained from the simulation of the geometry under consideration and the reference geometry. The parameters of reference geometry were given in Table I. Von-Mises stress is a sensible physical rendering to determine whether the strand has started to yield at any point subjected to an externally applied load. High von-Mises stress means the stress on these regions can lead to component failure. Low von-Mises stress means, the chance of failure is less for the same applied load.

The surface plot of the dispersal of maximum von-Mises stress of a monolithic Roebel strand (dimension: the inner fillet radius = 8 mm, outer corner is sharp, Roebel angle = 30°, strand width = 2 mm) shown in Fig. 10 was compared with [5] which also displayed a similar impression.

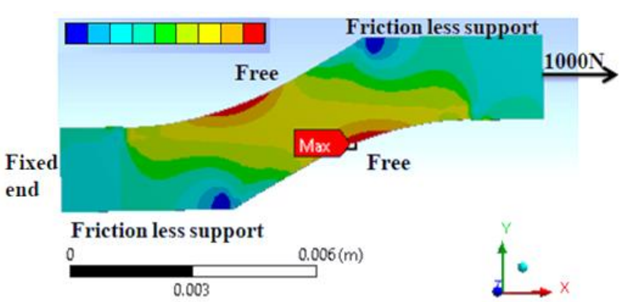

Fig. 10. The von-Mises stress distribution of a straight Roebel strand. The colour scale indicates the intensity and distribution of stress in the strand.

The finite element analysis of the twisted Roebel strand was performed, and the effects of the following cases were studied:

i) The variation of relative maximum von-Mises stress with variation in inner and outer fillet dimension

ii) The variation of relative maximum von-Mises stress with variation in inner radius when the Roebel angle changes

Relative width of 1 was considered for the 2 mm wide Roebel strand in both cases. In the first case, the Roebel angle was kept constant, and considered as 30°, and in the second case, the outer corner was considered as sharp. Also, the influence of the relative strand width on relative maximum von-Mises stress of a strand having Roebel angle 30° and outer and inner corner sharp was studied.

IV. Results and Discussions

The simulations were performed for all conditions mentioned above after varying each geometrical parameters. The maximum obtained von-Mises stress was noted and compared with the results reported in [5]. We found that in all cases the maximum von-Mises stress was concentrated at the inner corner of the Roebel strand.

Fig. 11 depicts the variation of relative maximum von-Mises stress with variation in the inner fillet dimension when the outer fillet dimension of the strand was considered as sharp, 2 mm, 4 mm and 6 mm respectively. When the dimension of inner fillet increased, the stress concentrated in this region reduced, which means that providing fillets increases the mechanical stability and life of Roebel strands exposed external mechanical loads [7]. Even though an increase in inner fillet dimension reduces the stress concentration, too much increase in its value increases the cross-over area and reduces the total number of strands that can be accommodated in a Roebel cable of given transposition length.

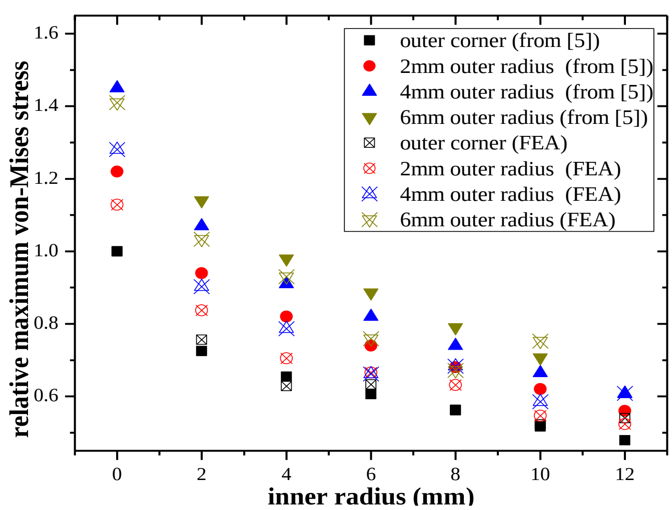

Fig. 11. Comparison of relative maximum von-Mises stress of a monolithic strand and the Roebel strand with normal twist. Data points labelled (from [5]) are the data obtained from work [5] and the data points labelled (FEA) are the simulated results of the twisted Roebel strand.

However, the effect of giving a fillet on the outer corner of the Roebel strand was converse. Increasing the fillet dimension at the outer corner adversely affected the expected strand performance as it increased the stress concentration in strands. Providing fillet at the outer corner of the Roebel strand removed some material from the reference geometry (model), which increased with fillet size. This reduced the strength of the strand, which is visible from its performance against externally

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applied loads. The normal twisting of the strand reduces the impact of stress. Increase in inner fillet dimension increased the degree of twist, and distributed the stress over a larger area, rather than concentrating it at the inner corner. The redistribution of stress enhance the performance of the Roebel strand against applied load. Even though the increase in outer fillet dimension affected the degree of twist of a Roebel strand, the strength of the strand was reduced since the available width of the strand (at the beginning of cross-over region) reduced due to filleting operation. Hence, it can be concluded that the magnitude of stress developed in a Roebel strand under an applied load depends not only on the geometrical parameters but also on the typical twisting of the strand. Because the variation in any parameter affects the position about which one strand overlaps the other, and consequently varies the degree of twisting of the Roebel strand. An average of 7.5%, 11% and 7.4% reduction in relative maximum von-Mises stress occurred for the 2 mm, 4 mm and 6 mm outer corner tapes, respectively due to the strand's natural twisting.

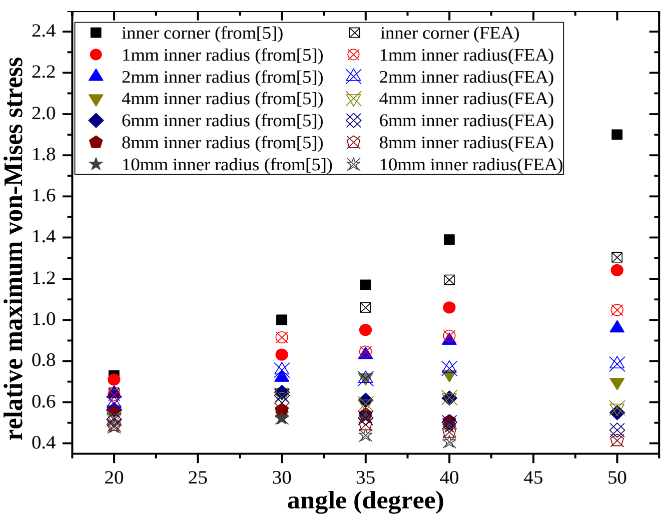

Fig. 12. The comparison of relative maximum von-Mises stress of a monolithic strand and a Roebel strand with normal twist. The effect of change in Roebel angle for various inner radii is shown. Data points labelled (from [5]) are the data obtained from work [5] and the data points labelled (FEA) are the simulated results of the twisted Roebel strand.

Fig. 12 shows the comparison of the simulated result of a twisted Roebel strand with the data obtained from [5]. The variation of relative maximum von-Mises stress with respect to the variation on the Roebel angle for various inner fillet radii is depicted in the figure. Though the Roebel angle changes, the relative maximum von-Mises stress increased up to an inner fillet dimension of 4 mm only. However, from 6 mm inner fillet onwards for the high value of Roebel angles, a reduction in relative maximum von-Mises stress occurred. Compared to the monolithic strand, the twisted Roebel strand exhibited lower stress values. From geometrical models, we noticed that any variation in Roebel angle causes a corresponding variation in the region overlap of strands which in turn influence the degree of twist. Twisting of the tape causes an inhomogeneous stress distribution compared to an untwisted one and results in the variation of the von-Mises stress [12] [13]. The stress state of the cable can be adjusted by pre-twisting the strands to improve the mechanical and transport performance [14].

Fig. 13 shows the comparison of the variation in relative maximum von-Mises stress at different relative width of a twisted and monolithic Roebel strand. The inner and outer corners of both strands were considered sharp in this case. As the relative width of the strand increased, the cross-over region became more rigid, and the strength of the strand increased. The applied load is distributed to a wider area, thereby reducing the relative von-Mises stress. In addition to the above phenomenon, the twisting of the strand also helps to reduce the developed stress. Even though an increase in width at the cross-over region increased the rigidity and stability of Roebel cables, too much increase in relative width took away the meander structure of the Roebel strand, thereby reducing its usage. It also reduced the total number of strands that can be mounted on a Roebel cable with given transposition length as each strand occupied more space. Relative width of just greater than one is enough for Roebel strands [5]. It is stated in [5] that the strand with Roebel angle 35^{o}, outer corner sharp and inner radius 6 mm is good if more number of strands have to be mounted in given transposition length.

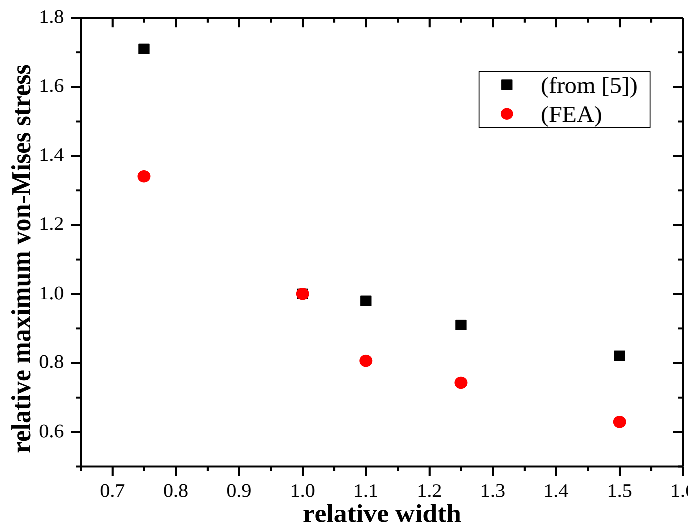

Fig. 13. The influence of relative width of the strand on relative von-Mises stress for a strand with both outer and inner corner sharp. A Roebel angle of 30^{o} is considered. Data points labelled (from [5]) are the data obtained from work [5] and the data points labelled (FEA) are the simulated results of the twisted Roebel strand.

From the above study, it was clear that the mechanical analysis of the Roebel strand is not complete or perfect if one neglects the natural twisting of the strand. Each parameter influences the mechanical stability of the Roebel cable; since a slight variation in any parameter influences the position at which one strand transpose over the other. Hence, while designing or optimizing the Roebel cable, it is essential to consider the effect of every parameter of the Roebel strand. The effect of strand's natural twist on the AC loss of a 14-strand Roebel cable was reported in the work [15]. Since it is not feasible to optimize the mechanical stability of the Roebel cable by varying each parameter and testing the effect in physically, mathematical modelling and simulation must be carried out.

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One of the essential inputs required for this was the relation between each parameter of the Roebel strand/cable. If such a relation can be made, then it becomes easy to model the cables and predict the stability of the cable against mechanical load via simulation. As mentioned earlier, as the performance of a Roebel cable is influenced by all the parameters such as thickness of HTS tape (t), width of HTS tape (W_t), width of Roebel strand (W_R), Roebel angle (φ), gap between stacks of strands at the straight section (W_c), width at the cross-over region (W_x), transposition length of the cable (L) and the number of strands in the Roebel cable (N), the relation helps to obtain the 3D model easily if any of the parameters are varied.

Generally, the parameters decided first, before designing a Roebel cable are the thickness of HTS tape (t), width of HTS tape (W_t), width of Roebel strand (W_R), Roebel angle (φ), width at the cross-over region (W_x) and the transposition length of the cable (L).

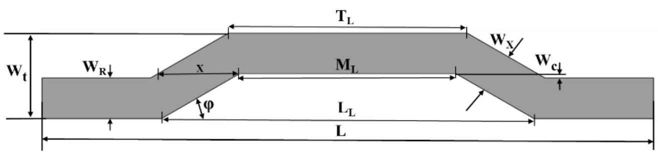

Fig. 14. Structure of a Roebel strand with all essential parameters marked.

Let the parameters of the geometrical shape that is punched off from the HTS tape to generate Roebel strand are the top length of the Roebel strand (T_L), middle length of Roebel strand (M_L) and the lower length of the Roebel strand (L_L). Any variation in the dimension of Roebel angle influences the geometrical shape to be punched off from the HTS tape to produce the Roebel strand. This in turn affects all the other parameters of the Roebel strand and influence the degree of twist. Like Roebel angle, the variation of any parameter influences the Roebel structure. Careful observation of the Roebel geometry reveals that the maximum number of strands that can be assembled in a Roebel cable of given transposition length depends on the longitudinal cross width (x). However, as the longitudinal cross width (x) depends on all other parameters, the following relations in Equations 1-6 can be used to obtain the maximum number of strands that can be occupied in a Roebel cable of given transposition length. The relations can also be used to obtain the dimension of any unknown parameter that is required to model the Roebel structure. Thus it becomes easy to model Roebel cables having strand's natural twist.

$$W_c = W_t - 2W_R \tag{1}$$

$$x = \frac{W_x}{\sin \varphi} \tag{2}$$

$$M_L = \left(\frac{L-2x}{2}\right) - (W_c / \tan \varphi) \tag{3}$$

$$T_L = M_L + 2\left(x - \left(\frac{W_R}{\tan \varphi}\right)\right) \tag{4}$$

$$L_L = M_L + \frac{2(W_R+W_c)}{\tan \varphi} \tag{5}$$

$$N = \frac{L_L}{x} + 1 \tag{6}$$

The above relations are formulated by assuming both the inner and outer corners of the strand are sharp. If the determined number of strands is non-integer, round it to the lowest integer. The above relations are valid only if the cross width is greater than or equal to strand width. However, the Roebel strand should always be made in such a way that the cross width is always greater than or equal to the strand width since the reduced cross width reduces the mechanical strength of the strand. Hence the above relations can be used to estimate any parameters while designing or modelling the Roebel cable.

V. CONCLUSION

Selecting the right geometric parameter is very important to produce a mechanically stable Roebel cable which will exhibit a long operational lifetime. In this work, a 14-strand Roebel cable was modelled, and the finite element mechanical analysis of its strand was performed when it was subjected to an external tensile load. In the first approach of the 3D analysis, all the other sublayers were neglected, and the strand was considered as a single material of thickness 0.1 mm, and the mechanical properties were assumed equal to the weighted average ratio of all layers in the HTS strand. However, the effect of normal twisting of the strand while it is assembled into a cable was considered. Results were then compared with another work where the analyses were performed on a monolithic Roebel strand. The influence of varying geometrical parameters such as Roebel angle, inner radius, outer radius and the relative width on the mechanical stability of twisted Roebel strand was simulated and compared with the result of a monolithic Roebel strand. We observed that the stress developed was less for twisted Roebel strand compared to the monolithic strand in all cases. An average of 7.5%, 11% and 7.4% reduction in relative maximum von-Mises stress occurred for a twisted Roebel strand (having outer corner sharp and inner radius 2 mm, 4 mm and 6 mm respectively) compared to a monolithic Roebel strand.

From the geometrical models, we noticed that the position and degree of twisting of a Roebel strand in a cable depended on all geometrical parameters of the Roebel cable. Relation between all the parameters of the Roebel cable was also made to make the 3D modelling of the actual Roebel cable easier. A small yet essential parameter to be considered while modelling and analyzing a Roebel cable is the degree of twist of its strand. The present work, however, overlooked the inner and outer fillet dimension while formulating the relation between the parameters of the Roebel cable. In future studies, these disparities can be avoided.

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Gijoy. S was born in Kollam, Kerala, India in 1985. He received the B. Tech degree in Mechanical Engineering from Cochin University of Science and Technology (CUSAT) in 2007 and M. Tech in Industrial Refrigeration and Cryogenic Engineering from University of Kerala in 2009.

From 2016 onwards, he is a research scholar in Mechanical Engineering Department at TKM College of Engineering, Kollam, Kerala, India. Since 2012, he has been an Assistant Professor with the Mechanical Engineering Department, Sree Chitra Thirunal College of Engineering, Trivandrum, Kerala, India. His research interests include superconductivity, electromagnetism, cryogenics, refrigeration and air-conditioning and thermal science.

Dr. K.E. Reby Roy was born in Trivandrum, Kerala, India in 1971. He received his B. Tech and M. Tech degrees in mechanical engineering from the University of Kerala, Trivandrum, in 1994 and 1996 respectively and the Ph.D. degree in mechanical engineering from IIT Madras, Chennai, India in 2003.

His areas of expertise include cryogenics, CFD, FEM, bio-engineering and superconductivity. He is a registered supervisor for doctoral studies in the University of Kerala, Trivandrum and the APJ Abdul Kalam Technological University, Trivandrum. He is currently Associate Professor, Department of Mechanical Engineering and Dean-Research and International collaborations of TKM College of Engineering, Kollam. He is engaged in collaborative research with many high-ranking universities around the globe and has many collaborative journal publications and funded projects to his credit.

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