CHAPTER 6

IMPROVED FINITE ELEMENT MODEL

6.1 INTRODUCTION

This finite element model takes up from the limitations where the previous representative sector model leaves. The present finite element model considers the individual wire geometry to be an ellipse on the plane perpendicular to core axis, whereas it would be a circle on the plane perpendicular to wire axis (helix). In reality these cross sections are bean shaped due to contact force with core even before loading but are idealized to elliptical cross sections initially. Unlike the earlier basic sector model, the complete assembly of wires with the core has been carried out for a full pitch using 3D solid (brick) elements. Further radial contact interfaces and associated frictional parameters, are included in the model. Prediction of strand response for axial loading has been attempted for the fixed – fixed and free – fixed end conditions.

6.2 ASSUMPTIONS AND METHOD OF APPROACH

A strand of straight core wire and one layer of six wires of the same configuration shown in Figure 5.1 has been modeled. In the previous analysis, the input in terms of applied extension was specified in the constraint equations imposed on the model. Using these constraints the finite element analysis was performed to predict the forces acting on the strand.
Unlike the earlier basic sector model, the complete assembly of wires with the core has been carried out for a full pitch length using 3D solid elements. The simple straight strand cable structure has been constructed using the ANSYS software. The effects of Poisson’s ratio and friction coefficient on the global response of the strand were also studied.

6.2.1 Extraction of the Finite Element Model

The geometry of the core has been obtained by a linear z-axis extrusion. Each wire has been generated by the extrusion of its cross section along a helix (multi linear curve) corresponding to the centroidal line of the wire. Three dimensional solid (brick) elements had been used for structural discretization. The model was developed for one pitch length and was then meshed using 3D solid elements as shown in Figure 6.1 (a). To consider the accuracy of results of the present finite element model, it was compared with experimental data reported by Utting (1987c), the theoretical model of Sathikh (1996) and FEM based non dimensional model of Ghoreishi (2007c). The geometric and material data were chosen from that of experimental study. The material modulus was considered to be 197.9 GPa. The effect of Poisson’s ratio is studied for two different values, 0 and 0.3. The diameters of the wire and core are 3.33 mm and 3.66 mm respectively with the wires laid up at a helix angle of 75.4°.

An available ‘Master- Slave node concept’ called ‘CERIG’ (ANSYS command) was used to define a rigid region. Multiple constraint equations to relate nodes in the rigid region are generated by this concept. In the present FE model, any plane cut perpendicular to the strand axis would contain nodes on the circular section of the core and those on the elliptical section of the wires. Nodes on the rigid plane which is the loading end of the strand was grouped together to form ‘Slave nodes’. A mass element with a
very small mass (to reduce inertia effect) containing single node called ‘Master node’ with six degrees of freedom (three translation and three rotation), was created on the axis of the core at a distance away from the slave nodes. This master node facilitates the axial loading. The slave nodes on the top surface of the wires and core were linked using rigid body elements to the master node which transforms the same axial displacement on slave nodes as defined to the master node. The Figure 6.1(b) is an illustration which shows the visibility of connection between the master node and the slave nodes with rigid links. The top view of the master node, positioned at the center of the cross section, is shown in Figure 6.1(c). The master node was so positioned away from the top surface as shown Figure 6.1(d) of the strand so that the radial force due to axial strain so emerged are minimal. This has been addressed in the model by positioning the nodes on any plane perpendicular to the strand axis to have a cyclic symmetry. The contact conditions between the wires and the core (wire/core contact) have been applied for the nodes situated near the helical lines of contact between them, thereby permitting relative movement. The effect of friction coefficient is studied for 3 different values, 0 (frictionless), 0.12 (nominal) and 0.5 (high). The boundary conditions required to simulate the loading for the strand model have been achieved as under:

i) The bottom end section of the cable is fully clamped by constraining all the degrees of freedom (d.o.f) of the nodes.

ii) In the case of fixed end loading, strand rotation is clamped by constraining all the d.o.f of the master node except for its translational d.o.f along strand axis.

iii) Unlike the fixed end loading, in the case of free end loading, strand rotation about strand axis is permitted on the master node.
Figure 6.1 Finite Element Mesh: (a) without master node (b) with master node (shown nearer to the top surface for clarity) (c) Top view showing the master node at the cross section center. (d) with master node (actual position from the top surface)
6.3 FINITE ELEMENT ANALYSIS AND DISCUSSION

The responses of the strand assembly in terms of axial load, torque, contact parameters, and stress distribution to static axial displacement under two different degrees of fixity for a simple 7-wire steel strand have been studied using this finite element model. A study with linear elastic, isotropic material model has been used for the purpose. Contact between the center and helical wires have been simulated using contact elements that allow positive pressure to be transferred between the surfaces. They can simulate general surface-to-surface contact with Coulomb friction sliding. A coefficient of friction of 0.12 was adopted from the experiment reports of Raoof and Hobbs (1988).

Preliminary simulations were performed with various finite element models of length up to two pitch for trade-off between the computational time and accuracy which justified the final selection of one pitch model used in this analysis. A strand axial strain in increments steps of 0.001 was applied upto a maximum strain value of 0.004 at the master node in the analysis and results have been compared with the following:

(i) Linear symmetric analytical model of Sathikh (1996),

(ii) Linear stiffness terms calculated from non-dimensional components of the stiffness matrix expressed by Ghoreishi (2007c), and

(iii) the experimental results of Utting (1987c).
6.3.1 Strand Axial Load and Moment -Fixed End Loading Case

Figure 6.2 shows the load response of the strand (at master node) to the axial strains for the fixed end conditions.

![Figure 6.2 Variation of strand axial load for Fixed end condition](image)

The predicted strand axial load from the present FEM, FEM (Ghoreshi et al) and the theoretical model were found to overestimate the test results and the respective deviations were found to be 4.28 %, 9.19% and 9.86% for a strain value of 0.0035, which corresponds to limiting strand load of 35kN in the test. It can be seen from Figure 6.2 that the present finite element analysis predicts closer to the test data in the linear region as given by Utting (1987c).
Figure 6.3  Strand response: Variation of torque with axial strain for fixed-end loading.

In the case of fixed end condition, as the ends are restrained from strand rotation, they induce torque during axial loading.

Figure 6.3 shows the torque variation as a function of axial strain. The results of the present FEM, FEM (Ghoreishi et al) and the theoretical model were found to deviate by 9.4%, 16.7% and 17.9% respectively from the test results, all for a strain value of 0.0035. It is observed that the axial and torsional response of all models were upper bound of which the present FEM work resulted closer to test data.

The effect of Poisson’s ratio and friction coefficient on strand axial force and moment in fixed end loading are shown in Figure 6.4 and Figure 6.5 respectively.
Figure 6.4 Strand axial load for change in Poisson’s ratio and friction coefficient in fixed end loading condition.

Figure 6.5 Strand moment for change in Poisson’s ratio and friction coefficient in fixed end loading condition.
The combined effect of varying Poisson’s ratio and friction coefficient on strand axial loading and strand moment is found to be insignificant (less that 2%) in fixed end loading case.

### 6.3.2 Strand axial load and moment - Free End loading case

In the case of free end, the ends of the strand are not restrained from angular displacement. The variation in strand rotation, strand axial load is plotted as a function of strand axial load and strand axial strain respectively (for all considered models) in Figure 6.6. and Figure 6.7. It is observed that the strand rotation of all models were lower bound of which both the FEM models deviated by a larger extent from the test data.

![Figure 6.6 Strand rotational response for free end loading](image)

The corresponding strand twist rate at strand load of 35kN was found to be 0.00275 rad/mm in the present work compared to the test value of 0.003 rad/mm. Likewise the results from the theoretical model of Sathikh and FEM (Ghoreishi et al) were found to be 0.00292 rad/mm and 0.00274 rad/mm respectively. The relative difference between the FEM models was found to be insignificant.
In the case of free end loading, the variation of strand load with respect to strand axial strain is shown in Figure 6.7. The result of the present FEM, FEM (Ghoreshi et al) and the theoretical model were found to underestimate the test result and the respective deviations were found to be 3.05 %, 0.4% and 1.84% for a strain value of 0.005. The limiting strand load in the linear region in the test data was reported to be 35kN at an axial strain of 0.005.

In general, it is confirmed that for the same strand axial strain, the helical wires with a free end condition carry less axial load than with the fixed end conditions.

Figure 6.7 Variation of axial load Free end condition

The effect of Poisson’s ratio and friction coefficient on strand axial force and strand twist rate in free end loading are shown in Figure 6.8 and Figure 6.9 respectively. The effect of Poisson’s ratio on the axial strand response as shown in Figure 6.8 has produced a variation of 6.8% and an insignificant variation with regard to the effect of friction.
Figure 6.8 Strand moment for change in Poisson’s ratio and friction coefficient in free end loading condition.

Figure 6.9 Strand twist rate for change in Poisson’s ratio and friction coefficient in free end loading condition.
Similarly the effect of Poisson’s ratio towards the strand twist rate response as shown in Figure 6.9 has produced a variation of 8.8% and an insignificant variation with regard to the effect of friction.

6.3.3 Stiffness matrix components

The elastic overall behavior of the structure can be expressed by four stiffness matrix components namely $F_\epsilon, M_\epsilon, F_\phi, & M_\phi$ which are pure tensile, torsion and coupling terms respectively. These components are computed for all the considered models and are tabulated in Table 6.1.

Table 6.1 Comparison of stiffness matrix components of various models considered.

<table>
<thead>
<tr>
<th>Model</th>
<th>$F_\epsilon$</th>
<th>$F_\phi$</th>
<th>$M_\epsilon$</th>
<th>$M_\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory (Sathikh et al)</td>
<td>11.46 MN</td>
<td>8.49 MN mm</td>
<td>8.49 MN mm</td>
<td>15.14 MN mm^2</td>
</tr>
<tr>
<td>FEM(Ghoreishi et al)</td>
<td>11.39 MN</td>
<td>8.46 MN mm</td>
<td>8.41 MN mm</td>
<td>15.67 MN mm^2</td>
</tr>
<tr>
<td>FEM(Present work)</td>
<td>10.87 MN</td>
<td>8.39 MN mm</td>
<td>7.88 MN mm</td>
<td>15.34 MN mm^2</td>
</tr>
<tr>
<td>Test( Utting, Jones)</td>
<td>10.43 MN</td>
<td>6.17 MN mm</td>
<td>7.21 MN mm</td>
<td>12.31 MN mm^2</td>
</tr>
</tbody>
</table>

It is observed that in general the stiffness components from all the considered models overestimate the test data. The Asymmetric nature of the coupling terms recorded by the test results is in better agreement with that of the present finite element model. This is because of the inclusion of frictional contact and Poisson’s effect in the present model.
Table 6.2 Variation of stiffness matrix components with respect to test data

<table>
<thead>
<tr>
<th>Model</th>
<th>Percentage variation of $F_e$ with Test</th>
<th>Percentage variation of $F_\varphi$ with Test</th>
<th>Percentage variation of $M_e$ with Test</th>
<th>Percentage variation of $M_\varphi$ with Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory (Sathikh et al)</td>
<td>-9.88</td>
<td>-37.60</td>
<td>-17.75</td>
<td>-22.99</td>
</tr>
<tr>
<td>FEM(Ghoreishi et al)</td>
<td>-9.20</td>
<td>-37.12</td>
<td>-16.64</td>
<td>-27.29</td>
</tr>
<tr>
<td>FEM(Present work)</td>
<td>-4.22</td>
<td>-35.98</td>
<td>-9.29</td>
<td>-13.89</td>
</tr>
</tbody>
</table>

The test results show that theoretical predictions underestimate strand extension under fixed end condition and overestimate it in the free end condition. The strand rotations of both FE models underestimate the test data.

6.3.4 Stress distribution in the strand

Figure 6.10 (a) shows a radial line on the mid section of the strand assembly connecting the extreme ends of two opposite wires passing through the centre of the core and wires.

Figure 6.10(b) shows the axial stress distribution measured along a radial line. The stress distributions were estimated at the mid section of the strand assembly, which is free from the end effects.
Figure 6.10  Stress distribution along the radial line for both Fixed and Free end conditions: (a) radial line on the cross section of the strand assembly (b) axial stress distribution (c) von-Mises stress distribution
In case of fixed end condition the core section experiences uniform axial stress distribution for all strain values except for the contact ends with the wire where the stresses dip due to local contact pressure. Also, the axial stresses in the wire tend to decline linearly outwards from their contact ends due to the curvature effects of the wire. In case of free end loading, the axial stress distribution is uniform in the core except for the contact ends. The axial stress along the radial line from the contact ends towards the outer edges of the wire is observed to be decreasing steeply.

Figure 6.10 (c) shows the von-Mises equivalent stress distribution along the radial line. In case of fixed end condition, the core section experiences near equal stress distribution at all locations except at the contact ends where the stresses peak signifying the nearness / onset of local plastic deformation. Also, the von-Mises stress in the wire tends to decline linearly outwards from their contact portion along the radial line. In case of free end loading, the difference in von-Mises stress values between the center and contact ends of the core widens with increase in axial strains. Also, the stress values in the wire consistently experience the least value for all axial strains at a radial distance of 4.2mm (whereas the wire center is at 3.49mm) from the core centre, as against the outer ends of the helical wires. This effect is in response to the absence of torque in free end condition by means of free rotation.

In the present work, the contacts between the core and the helical wires have been simulated using finer contact elements between the surfaces. The contact elements used allow positive pressure to be transferred between the contacting surfaces and they can simulate general surface to surface contact with sliding friction.
Figure 6.11 Maximum contact pressure for both degrees of fixity

Figure 6.11 shows the distribution of contact pressure for three different values of friction coefficient considered for both fixed end and free loading. The influence of friction coefficient on contact pressure is insignificant (0.2%) in fixed end loading while it is found to be 8.0% in the case of free end loading. Due to unwinding and slight straightening of the helical wires the contact effects are less significant in free end case.

A small relative movement exists between the two contact surfaces due to the tendency of the helical angle to change when loaded. Figure 6.12 (a) and (b) show the contact sliding distance (slip) for varying friction coefficient for both loading conditions respectively. The frictionless model (friction coefficient = 0), resulted in large slip at increased axial strain levels in comparison to two other frictional models (friction coefficient =0.12 and 0.5) for both the loading cases. However between them for frictionless condition, the slip is relatively larger in free end loading case for all strain levels because of unwinding nature of the helical wires.
From these figures it can be seen that friction has a tendency to reduce the relative movement and causes additional shear stresses between the two contact surfaces. It was found from this analysis that friction only affects a very localized contact area. It hardly has any effect on the global behaviour of the strand.

Figure 6.12  Contact Sliding distance for both degrees of fixity: (a) fixed end case (b) free end case
6.3.5 Wire Tension

Figure 6.13 (a) and (b) presents the tension in a helical wire for various axial strains under fixed and free loading conditions.

![Graph showing wire tension vs. axial strain for fixed and free end conditions](image)

Figure 6.13 Variation of Wire tensions: (a) Fixed end condition, (b) Free end condition
The FEM results exhibit the non-linear distribution of wire tension. It was observed that within linear limits each of the 6 (helical) wires carry 14.0% and 9.8% of total strand load for fixed and free end loading conditions respectively; while the test results recorded the tension in each wire as 14.3% and 10.2% of the total strand load for fixed and free end loading conditions respectively. The findings using Sathikh model predicted the same as 14.0% and 9.2% respectively for fixed and free end loading.

6.4 CONCLUSION

The following are the observations of the improved finite element model:

(i) In the case of fixed end loading, the predicted strand axial load from the present FEM, FEM (Ghoreshi et al) and the theoretical model were found to overestimate the test results and the respective deviations were found to be 4.28% (6.24% for Basic sector FEM), 9.19% and 9.86% for a strain value of 0.003. The present finite element analysis predicts the response closer to the test data in the linear region as given by Utting (1987c).

(ii) In the case of fixed end condition, as the ends are restrained from strand rotation, they induce torque during axial loading. The torque variation as a function of axial strain obtained from the present FEM, FEM (Ghoreshi et al) and the theoretical model were found to deviate by 9.4%, 16.7% and 17.9% respectively from the test results, all for a strain value of 0.0035 which corresponds to limiting strand load of 35kN in the test.
(iii) It is observed that the axial and torsional response of all models were upper bound of which the present FEM work resulted closer to test data.

(iv) The combined effect of varying Poisson’s ratio and friction coefficient on strand axial loading and strand moment is found to be insignificant (less that 2%) in fixed end loading case.

(v) In the case of free end loading, the ends of the strand are not restrained from angular displacement. It is observed that the strand rotation of all models were lower bound of which both the FEM models deviated by a larger extent from the test data. The variation in the strand twist rate at strand load of 35 kN in the present model was found to be 8.3% in comparison with the test value. Likewise the variation of results from the theoretical model of Sathikh and FEM (Ghoreishi et al) were found to be 2.6% and 8.6% respectively. The relative difference between the FEM models was found to be insignificant.

(vi) In the case of free end loading, the variation of strand load with respect to strand axial strain obtained from the present FEM, FEM (Ghoreshi et al) and the theoretical model were found to underestimate the test result and the respective deviations were found to be 3.05 %, 0.4% and 1.84% for a strain value of 0.005. The limiting strand load in the linear region in the test data was reported to be 35kN at an axial strain of 0.005.
In general, it is confirmed that for the same strand axial strain, the helical wires with a free end condition carry less axial load than with the fixed end conditions. Therefore the linear limit is reached at a lesser axial strain in the fixed end case.

In the case of free end loading the effect of Poisson’s ratio on the axial strand response has produced a variation of 6.8% and an insignificant variation with regard to the effect of friction. Similarly the effect of Poisson’s ratio towards the strand twist rate has produced a variation of 8.8% and an insignificant variation with regard to the effect of friction.

The four stiffness matrix components representing the overall elastic behavior of the structure were computed and compared for various models. The error of symmetry between the coupling terms derived from the present work was found to be 6% and was predicting results closer to the test values.

The results from the overall strand responses with regard to stiffness of the present work for various loading cases indicated a very good correlation with the experimental values.

The stress distributions were estimated at the mid section of the strand assembly, which was free from the end effects. The peak von-Mises stress, for all strains, are located very near to the contact lines that are apparently caused by the local contact effect. This confirms the tendency to the plastic
yielding at contact location in both free and fixed end conditions.

(xii) The von-Mises stress in the helical wire consistently experience the least value for all axial strains at a radial distance of 4.2mm (whereas the wire center is at 3.49mm) from the core centre, as against the outer ends of the helical wires. This effect is in response to the absence of torque in free end condition by means of free rotation.

(xiii) The distribution of contact pressure for three different values of friction coefficient was considered and studied for both fixed end and free loading. The influence of friction coefficient on contact pressure is insignificant (0.2%) in fixed end loading while it is found to be 8.0% in the case of free end loading. Due to unwinding and slight straightening of the helical wires the contact effects are less significant in free end case.

(xiv) The contact sliding distance (slip) for varying friction coefficient for both loading conditions were reported. The frictionless model (friction coefficient =0), resulted in large slip at increased axial strain levels in comparison to two other frictional models (friction coefficient =0.12 and 0.5) for both the loading cases. However between them for frictionless condition, the slip is relatively larger in free end loading case for all strain levels because of unwinding nature of the helical wires.

(xv) The wire tension was also predicted in the present work. It was observed that within linear limits each of the six
(helical) wires carry 14.0% and 9.8% of total strand load for fixed and free end loading conditions respectively; while the test results recorded the tension in each wire as 14.3% and 10.2% of the total strand load for fixed and free end loading conditions respectively. The findings using Sathikh model predicted the same as 14.0% and 9.2% respectively for fixed and free end loading.

In general, the present of FEM model with regard to stiffness components indicated a good correlation with the experimental findings.