

Structural Analysis of the Progressive Die Bending Process for a High-Temperature Superconductor Stacked in Conduit Conductor

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1. Introduction

The toroidal field magnet of the Korean compact fusion device K-CPD is being designed around REBCO coated conductors, which sustain a useful current density at fields well beyond the reach of niobium based conductors. The conductor examined here is a stacked in conduit conductor (SICC), in which non transposed tapes are stacked, capped, wrapped by a double helix and enclosed in a stainless steel jacket, and it is the leading candidate for the magnet of that device. Stacking without transposition avoids the twisting that the flat geometry of a coated conductor makes difficult, and conductors of this type have been studied for fusion magnet applications [1]. The penalty is a bending response that differs between the two principal axes of the section. The device is specified with a major radius of 3.5 m, a minor radius of 1.0 m, a toroidal field of 6.3 T and a peak field of 18.0 T [5].

Winding the conductor into a coil imposes a curvature on the tape stack, and the REBCO layer is the part of the assembly least able to tolerate it. Reported strain limits depend on the criterion applied and on the tape. Taking the strain at which the critical current falls by 5 percent, measurements on tapes from three producers give 0.28 to 0.29, 0.40 to 0.43 and 0.50 to 0.55 percent [3]. Taking instead the irreversible strain limit, the strain beyond which the critical current does not recover on unloading, five manufacturers span 0.45 to 0.72 percent at 77 K in self field [4], while a survey of five further tapes reports a typical value near 0.4 percent [2]. The two criteria differ because the critical current falls reversibly before the loss becomes permanent. The degradation criterion is the more restrictive of the two and is adopted here, since the conductor has to carry its design current in the wound state rather than merely recover it on unloading. The permissible bending radius of the conductor is set by the strain reaching the tape rather than by the strength of the jacket, and that strain is not accessible to measurement during forming because the stack is enclosed by the cap, the helix and the jacket.

Winding of this conductor has previously been examined with DEFORM-3D using an idealised model in which a circular former is pressed against it in a single stroke [5]. That study reported the von Mises effective

strain of the stack and the relative displacement of the individual stacks, and it noted that the effective strain aggregates the axial, contact and frictional contributions, so that the axial strain governing the tape would lie below the reported values. The axial component was not separated, and the margin against the tape criteria was therefore bounded from above rather than quantified. The idealised loading also differs from the process adopted for the coil, in which the conductor is pressed in small increments and fed through the dies by their rotation between increments, so that every section passes the loaded contact repeatedly.

This paper analyses that process ahead of the bending test on the prototype conductor. The model reproduces the incremental press and rotation sequence, and the results reported here cover the first two of the five increments of the forming schedule, which carry the conductor to a bending radius of 2.836 m. The axial strain of the outermost superconducting layer is compared with the estimate that beam kinematics supplies and with the reported tape criteria, and the shape the conductor takes under the incremental loading is examined.

2. Conductor and bending process

2.1. Conductor configuration

The conductor is shown in Fig. 1. A stack of REBCO tapes occupies the centre of the section. A cap encloses the stack on its upper and lower faces, a double helix wound from a flat strip surrounds the cap, and a stainless steel jacket of rounded square section closes the assembly. The jacket is type 316L, the cap is type 304 stainless steel and the helix is oxygen free copper C10100. The helix is a two start winding whose strands are offset by half a pitch, and its axial fill factor is 0.78. Both the cap and the helix are symmetric about the mid plane of the section, so the neutral axis of the assembly coincides with its geometric centre. The modelled length of the conductor is 500 mm.

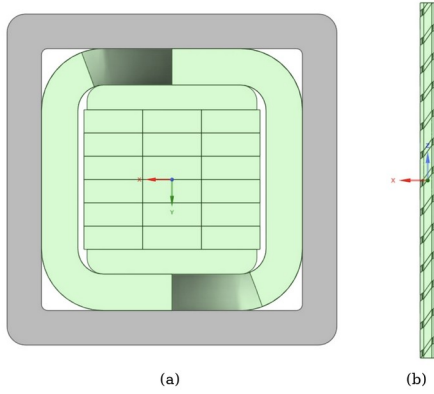


Fig. 1. Cross section of the conductor (a) and longitudinal view of the double helix (b). The tape stack is divided into three columns and six layers, the outer layer on each side being copper stabilizer.

Dimensions of the jacket, the cap and the helix belong to the conductor development programme and are not reported here. The quantities that enter the analysis are the height of the cavity left for the tape stack and the internal structure of the stack itself, and both are given below.

2.2. Structure of the HTS stack

The stack is divided into eighteen blocks, three across the width and six through the thickness. The three blocks that adjoin the cap on each side are copper and represent the stabilizer placed at the outside of the stack for current sharing and thermal stability. The remaining twelve blocks represent the coated conductor tapes and are assigned an aluminium alloy as a structural surrogate, for the reason set out in Section 3.6.

Since the outer layer is not coated conductor, the outermost superconducting layer is the second of the six. Because the six layers divide the stack height equally, the distance c from the neutral axis to the outer face of that layer is one third of the stack height rather than the one half that the stack envelope would give. Table I lists the values.

Table I: Structure of the HTS stack

Quantity	Value
Blocks across the width	3
Layers through the thickness	6
Outer layer on each side	Cu stabilizer
Inner layers	coated conductor
Stack height	11.300 mm
Layer height	1.883 mm
Stack envelope, half height	5.650 mm
Distance to outermost SC layer, c	3.767 mm

Two qualifications apply to c . The superconducting film lies within the thickness of an individual tape rather than at the face of the layer, so the true distance is marginally smaller and the value used is conservative.

Each layer in the model is an equivalent block representing several physical tapes and does not resolve them individually, so the outer face of the layer is taken as the reference.

2.3. Progressive die bending process

Three dies of radius 50 mm are used, arranged as in Fig. 2. The centre die presses the conductor at the mid section and two support rollers are placed at plus and minus 150 mm, which gives a half span of 150 mm and an overhang of 100 mm at each end of the modelled length. The conductor is bent about the axis parallel to the cap faces, which is the orientation imposed by the coil winding. The tape stack is wider than it is tall, so bending about the orthogonal axis would place the outermost superconducting layer further from the neutral axis and would give a larger minimum radius. That orientation is not considered here.

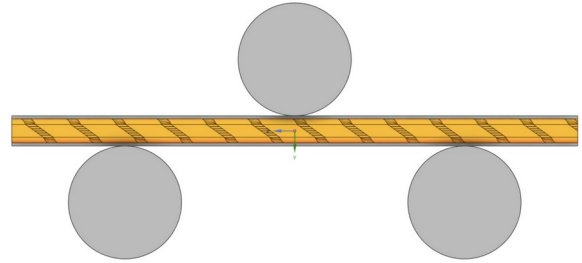


Fig. 2. Arrangement of the three dies, with the jacket rendered transparent so that the double helix is visible. The centre die presses in the y direction and all three rotate about the x axis, which feeds the conductor along z through contact friction.

One forming increment consists of a press of the centre die followed by four rotations of the three dies of 80 degrees each, in the sequence positive, negative, negative, positive. The feed produced by one rotation is the product of the die radius and the rotation angle in radians, which is 69.81 mm. The four rotations carry the conductor to plus 69.81 mm, back to the origin, to minus 69.81 mm and back to the origin, so that every section within the loaded region passes the contact point in both directions and the conductor returns to its starting position at the end of the increment. With an overhang of 100 mm the conductor still projects 30.19 mm beyond the roller at the extreme of the feed. Fig. 3 shows the history of the five increments of the schedule and marks the range covered by the present analysis.

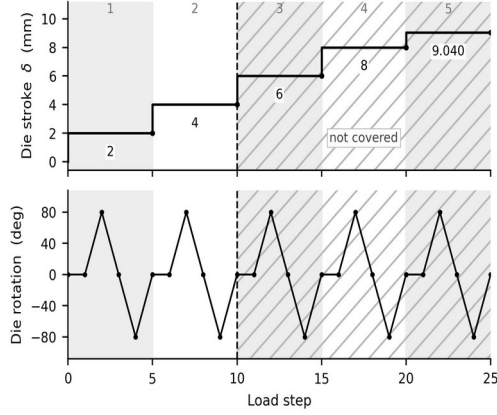


Fig. 3. Die stroke and die rotation over the twenty five load steps. Each increment is a press followed by four rotations that return the conductor to its starting position. The hatched region marks the increments that the present analysis does not cover.

The rotation angle was chosen so that the conductor is fed as far as possible while remaining engaged with all three dies. Bending is applied in increments rather than in a single stroke so that the indentation generated locally beneath the die at each press is redistributed along the length by the following rotations before the next press is applied.

2.4. Minimum bending radius

Two definitions of the minimum bending radius are in use. Experimentally it is the smallest radius at which the critical current of a bent sample degrades by less than a stated fraction, commonly five percent, and for bare tapes that condition is reached at radii of a few millimetres [3]. That definition is direct but it requires a sample, and for a cable it requires a sample of the assembled cable. At the design stage, before such a sample exists, the radius is obtained instead from beam kinematics. The axial strain of a fibre at a distance c from the neutral axis of a bent section is c divided by the radius, so that

$$R_{min} = \frac{c}{\epsilon_{allow}} \quad (1)$$

The allowable strain in (1) is not a single number. Under the degradation criterion adopted in Section 1 the reported values span 0.28 to 0.55 percent across manufacturers [3], and a characterisation of the tape actually used is required before a design limit is fixed. Table II lists the radius at 0.3, 0.4 and 0.5 percent, which are the lower end, the middle and the upper end of that range, evaluated both at the stack envelope and at the outermost superconducting layer.

Table II: Minimum bending radius

ϵ_{allow}	c at stack envelope	c at outermost SC layer
0.003	1.883 m	1.256 m
0.004	1.413 m	0.942 m
0.005	1.130 m	0.753 m

The lowest of the three is adopted as the design basis, since it corresponds to the most strain sensitive of the tapes reported, and a minimum bending radius of 1.256 m is taken as the design target of the forming schedule. Locating the governing fibre at the outermost superconducting layer rather than at the stack envelope relaxes the requirement by one third at every value, so the copper stabilizer that is present for electrical reasons also carries a mechanical benefit.

Equation (1) is a first order estimate. It neglects the distortion of the cross section under bending, the indentation generated beneath the die and any accumulation of plastic strain over the repeated passes of the forming process, and it assumes that the stack is rigidly coupled to the surrounding structure. Whether the strain that actually reaches the tape lies below or above the value that (1) assumes is the question the analysis is set up to answer, and the results reported here address it over the range of curvature that has been analysed. Whether the limit is binding in practice depends on the tightest curvature in the coil winding, which follows from the magnet geometry and lies outside the present scope.

3. Finite element model

3.1. Model and solution scheme

The analysis was carried out in ANSYS Mechanical 2025 R2 as a static structural problem with large deflection enabled, a sparse direct solver and a full Newton-Raphson scheme with line search. The three dies are treated as rigid bodies driven through pilot nodes. The conductor length lies along the z axis, the pressing and bending direction along y , and the die rotation axis along x , so that rotation of a die about x produces a tangential velocity with a z component at the contact point.

The process is represented by five increments of five load steps each, giving twenty five load steps. Table III lists the schedule. The first four increments advance the stroke in steps of 2.0 mm and the fifth completes the stroke that the mapping of Section 4.1 gives for the target radius. No increment adds more than 2.0 mm, which limits the indentation developed beneath the die before the following rotations redistribute it. The assembly was built up in stages, the internal bodies and their contact pairs being added a few at a time with convergence and the symmetry of the stress distribution checked at each stage, because introducing all of them at once prevents convergence. The results reported here cover the first two

increments, that is load steps 1 to 10, which terminate at a radius of 2.836 m. The remaining three increments are the subject of continuing work.

Table III: Forming schedule

Inc.	Load steps	δ (mm)	$\Delta\delta$ (mm)	h (mm)	R (m)	c/R
1	1 to 5	2.000	2.000	1.989	5.656	0.00067
2	6 to 10	4.000	2.000	3.979	2.829	0.00133
3	11 to 15	6.000	2.000	5.968	1.888	0.00200
4	16 to 20	8.000	2.000	7.958	1.418	0.00266
5	21 to 25	9.040	1.481	8.992	1.256	0.00300

3.2. Mesh

Quadratic hexahedral elements are used for the jacket, the cap and the stack blocks, and quadratic tetrahedra for the double helix. Quadratic elements are used throughout because linear elements overestimate bending stiffness through shear locking, which would bias the quantity of interest. Three elements are placed through the jacket wall, and an edge sizing with an even number of divisions along the conductor puts a node plane exactly at the mid section, which the constraint scheme of Section 3.4 requires. The model contains 414,866 nodes and 244,759 elements.

3.3. Materials

Table IV lists the material models. Isotropic hardening is applied to all four materials, and the copper is taken in the annealed condition delivered by the drawing and annealing route used for the helix.

Table IV: Material models

Material	E (GPa)	Yield (MPa)	Yield strain	Applied to
STS 316L	193	290	0.00150	Jacket
STS 304	193	215	0.00111	Cap
Cu C10100	117	69	0.00059	Helix, outer stack blocks
Al-6061-O	68.9	55	0.00080	Inner stack blocks

The yield strain of every material is below the target strain of 0.00300, so all components are plastic over most of the forming range. The strain reported for the stack is consequently the total mechanical strain, the sum of the elastic and plastic parts, since the elastic part alone would represent a small fraction of the deformation and the reported tape criteria are defined on total strain.

3.4. Boundary conditions

At the instant loading begins the only closed contacts have their normal along the pressing direction, and the tangential stiffness of a frictional contact is proportional to a normal force that is still zero. The model therefore has no restraint against axial or lateral translation, nor against rotation about the pressing and length axes, and

explicit constraints are required. The lateral displacement of the two end faces is held throughout the analysis, and the axial displacement of the mid section is held during the first load step only, being released afterwards so that the feed produced by the die rotation is not obstructed. The mid section constraint is admissible because the structure and the loading are symmetric about that plane and the axial displacement there is zero by symmetry.

Both constraints were checked against the die reaction at the end of the first press. Against a die reaction of 12,000 N in the pressing direction, the mid section constraint carries 45 N and the end face constraint 31 N, which are 0.375 and 0.26 percent, so neither participates in the load path.

3.5. Contact

The contact between each die and the jacket is frictional with a coefficient of 0.25 and is formulated with the augmented Lagrange method. Because the dies rotate through a large angle, the contact has to be allowed to re-establish its pairing as the surfaces move relative to one another. If the pairing determined at the start of the analysis is retained, the contact elements continue to track target elements that the rotation has carried away, the conductor loses its lateral restraint and the solution diverges. The option that freezes the pairing is therefore disabled explicitly rather than left to the program default.

Internal interfaces between the jacket, the double helix, the cap and the stack blocks are bonded. Interface friction coefficients and the residual radial compression left by the jacketing process are not available, and a bonded treatment is the conservative choice in that situation, since relative slip between the components can only reduce the strain transferred to the stack. The consequence for the result is discussed in Section 4.4.

3.6. Load path decomposition

A first order decomposition of the assembly bending stiffness identifies which components govern the deformation. Each component is treated as a prismatic body bending about the neutral axis of the conductor, with the parallel axis term included, and the double helix is represented by an equivalent sleeve whose wall is scaled by its axial fill factor.

Table V: Bending stiffness decomposition

Component	EI ($\times 10^6$ N·mm ²)	Share
Jacket	4,989	75.3 %
Double helix	969	14.6 %
Cap	492	7.4 %
HTS stack	177	2.7 %
Total	6,627	

The jacket and the double helix together carry 90 percent of the bending stiffness, so the curvature imposed on the conductor is set by the conduit and not by its contents. The stack carries 2.7 percent and is therefore a mechanically passive passenger whose strain is dictated by the surrounding structure rather than by its own constitutive behaviour, which is what permits the aluminium surrogate of Table IV. The quantity extracted is the axial bending strain, which follows from the curvature and the position of the fibre, and the constitutive model of a component supplying 2.7 percent of the stiffness has correspondingly little influence on the curvature. The stress reported for the stack is not representative of a real tape, whose modulus and yield strength are both much higher, and is not used in the assessment.

Within the stack the copper layers carry 80 percent of the bending stiffness of the stack, because they are the layers furthest from the neutral axis. The stabilizer forms a stiff outer skin over the coated conductor layers, which is the structural counterpart of the kinematic effect described in Section 2.2.

4. Results and discussion

4.1. Die stroke to bending radius mapping

The bending radius is not prescribed directly but follows from the die stroke, so the mapping was established before the strain results were interpreted. Because the deformed conductor is held at three points of known position, the radius follows from circular geometry alone. With a half span a and a mid span deflection h of the conductor neutral axis,

$$R = \frac{a^2 + h^2}{2h} \quad (2)$$

Equation (2) contains no material property and no bending stiffness, and is therefore independent of the constitutive model of any component.

The deflection h in (2) is that of the conductor neutral axis and not the stroke of the die, and the two differ by the local indentation of the jacket wall beneath the die. They were related by measurement at the end of the first increment, after the four rotations had returned the conductor to the origin, since the intermediate states carry a feed offset and are not symmetric. At a stroke of 2.000 mm the vertical displacement of the conductor neutral axis was 1.9893 mm at the mid section and below 2×10^{-13} mm at both rollers. The vanishing displacement at the rollers confirms that the conductor remains seated and that the deformed shape is symmetric about the mid section. Hence

$$h = 0.9947 \delta \quad (3)$$

so that at the first increment the local indentation absorbs 0.535 percent of the imposed stroke. Substituting the stroke directly into (2) in place of h would place the radius at 5.626 m against 5.656 m obtained with the measured deflection, a bias of 0.53 percent. Equations (2) and (3) give the schedule of Table III. Since the contact pressure grows with the stroke, the factor of (3) was re-evaluated at the end of each increment as it completed and the remaining strokes were adjusted so that each increment terminates at its target radius.

The same measurement provides a check on the global stiffness of the model. For a simply supported span of 300 mm carrying a central load of 12,000 N, elementary beam theory with the assembly stiffness of Table V gives a mid span deflection of 1.02 mm, against the 1.99 mm measured. The outer fibre of the jacket at the corresponding curvature carries a strain of 0.0024 against a yield strain of 0.0015, so the jacket is already plastic at the end of the first press and a deflection of roughly twice the elastic value is what the measurement should return. Scaling that strain down to the yield value places first yield of the jacket outer fibre at a bending radius of 9.0 m, so the conductor is plastic over the whole of the forming schedule. The stiffness decomposition, the constraint scheme and the measured deformation are therefore mutually consistent.

The measurement was repeated at the end of the second increment. At a stroke of 4.000 mm the deflection of the neutral axis was 3.9702 mm, so the factor of (3) falls from 0.9947 to 0.9926 and the share of the stroke absorbed by the local indentation grows to 0.745 percent. The growth is consistent with the die reaction, which rises from 12,000 N at the end of the first press to 16,182 N at the end of the second. The bending radius obtained from (2) is 5.656 m at the end of the first increment and 2.836 m at the end of the second, the latter slightly above the 2.829 m that Table III plans with the nominal factor.

4.2. Axial strain in the HTS stack

The total mechanical axial strain of the tape stack was extracted at the end of each increment. Table VI lists the maximum together with the quantities that enter the kinematic estimate. It reaches 0.158 percent at 5.656 m and 0.547 percent at 2.836 m. Between the two increments the strain therefore grows by a factor of 3.46 while the imposed curvature grows by 1.99, so the strain rises appreciably faster than the curvature the die stroke prescribes.

Equation (1) evaluated at the outermost superconducting layer with the radius of (2) gives 0.067 and 0.133 percent for the two increments. The computed strain exceeds these values by factors of 2.4 and 4.1. Part of the difference follows from the concentration of curvature examined in Section 4.3. Substituting the local radius measured beneath the centre die in place of the span radius reduces the factor at the second increment from 4.1 to 2.0, so the concentration accounts for about

half of the discrepancy and not for all of it. The maximum lies at the lateral extreme of the stack rather than at its upper or lower face, so distortion of the cross section contributes to the remainder rather than bending alone. Against that reading, the local radius is itself obtained from a profile sampled every 6.25 mm and fitted over a window of 22 mm, which understates the curvature if it peaks over a shorter length, so part of the residual factor may follow from the sampling.

What is reported is the total mechanical strain of the metallic surrogate, whose yield strain is 0.080 percent, so plastic strain accumulates over the repeated passes of the forming process. A coated conductor is stiffer than the surrogate and would follow the section kinematics more closely, and the strain reported here is therefore an upper bound on what the tape experiences. Taken with the bonded internal interfaces discussed in Section 4.4, the value bounds the tape strain from above on two counts.

Table VI: Bending radius and axial strain of the stack

Quantity	Increment 1	Increment 2
Die stroke (mm)	2.000	4.000
Neutral axis deflection (mm)	1.9893	3.9702
Span radius from (2) (m)	5.656	2.836
Local radius at mid span (m)	2.995	1.412
Die reaction at the press (N)	12,000	16,182
c/R from the span radius	0.00067	0.00133
c/R from the local radius	0.00126	0.00267
Computed axial strain	0.00158	0.00547

4.3. Curvature concentration and redistribution by the rotation

The bending radius returned by (2) is an average over the span and assumes a circular arc. Neither holds for the computed shape. Fig. 4 gives the profile of the tension face over the loaded region together with the local curvature obtained from it. Because that profile lies on the tension face and not on the neutral axis, its mid span value falls short of the deflection of Table VI by the compression of the section beneath the die, an offset that leaves the curvature unchanged. At the end of the second increment the radius beneath the centre die is 1.412 m against the 2.836 m that (2) returns, and the curvature falls to a small fraction of its peak beyond about 100 mm from the mid section. That extent is comparable with the 69.81 mm of feed that one rotation produces in each direction, which sets the length of conductor carried through the loaded contact within an increment.

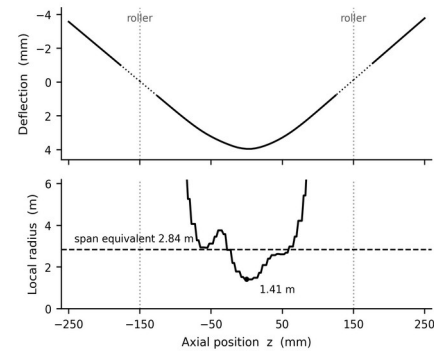


Fig. 4. Deflection of the tension face over the loaded region and the local curvature obtained from it, at the end of the first increment, immediately after the press of the second increment and after the four rotations that close it.

Comparing the profile taken immediately after the press with the profile taken after the four rotations isolates the effect of the rotation. The peak curvature falls from 0.852 to 0.712 per metre and the full width at half the peak grows from 55 to 80 mm, while the deflection at the mid section changes by less than one percent. The rotations therefore redistribute the bend along the length rather than deepen it, which is the behaviour the incremental scheme is intended to produce.

An independent reading of the strain history supports the same conclusion. Over those four load steps the maximum axial strain of the stack falls from 0.636 to 0.547 percent, a reduction of 14 percent, and the first increment gives a reduction of 18 percent over its corresponding steps. Two quantities drawn from different fields therefore agree to within three percentage points.

Redistribution is nevertheless partial. Against unity for a circular arc, the ratio of the span radius to the local radius stands at 2.45 immediately after the press and at 2.02 once the rotations are complete. The residual concentration follows from the load configuration. In three point bending the moment is largest at the centre die and falls to zero at the rollers, and the jacket outer fibre reaches its yield strain at a bending radius of 9.0 m as Section 4.1 shows, so permanent curvature can form only over the central part of the span where the moment exceeds that value. The rotations move material through that region but do not extend it, and within the feed range reproduced here they cannot carry the bend to the rollers.

The consequence for the strain limit is that the tape is governed by the curvature it meets beneath the die and not by the span average that (2) returns. A minimum bending radius fixed from (1) at the target radius of the coil therefore underestimates the strain reached during forming. Taken with the bonded interfaces and the metallic surrogate, which both act in the opposite direction, the strain in the tape is bracketed between 0.133 and 0.547 percent at the second increment, an interval that spans the range of the degradation criterion quoted in Section 1 rather than resolving against it.

Narrowing that bracket requires a frictional treatment of the internal interfaces and a tape characterisation, and is the substance of the work that follows.

4.4. Limitations of the analysis

The forming schedule was not completed. The results cover the first two increments, which reach a radius of 2.836 m, against the design target of 1.256 m. Measured in curvature, to which the bending strain is proportional, the analysed range spans 44 percent of the target, and the kinematic strain at the outermost superconducting layer rises from 0.067 to 0.133 percent over that range against the 0.300 percent assumed at the target radius. Two analysed states do not establish how the ratio of the computed strain to the kinematic strain behaves with curvature, so no extrapolation to the target radius is made here. The remaining increments are required before the margin against the tape criteria is established.

Three further limitations bound the interpretation. The internal interfaces are bonded, so the conductor deforms as a monolithic body and the strain reported for the stack is the upper bound of what the tape would experience. Relative slip between the stack, the cap and the helix allows each block to bend in part about its own mid plane and can only reduce the strain, so the assembled conductor can only perform better than the analysis indicates. Quantifying the reduction requires a frictional formulation of the internal interfaces together with the friction coefficients of the internal surfaces and the residual radial compression left by the jacketing process. Introducing a frictional interface without the assembly preload would leave the normal force to be generated by the bending alone, which would understate the shear transfer and would be less representative than the bonded bound rather than more accurate.

The tape stack is represented by a metallic surrogate. The decomposition of Table V shows that the surrogate does not materially affect the curvature, and the axial strain extracted is therefore representative, but the stress within the stack is not, and the strain concentration between the layers of a real laminated tape is not resolved.

The allowable strain spans a range rather than a single value, depends on the criterion applied and is specific to the manufacturer and the tape architecture [2]-[4]. A characterisation of the tape actually used in the conductor is required before the minimum bending radius is fixed as a design requirement.

A mesh sensitivity study is not included. Quadratic elements with three through the jacket wall were used for the reason given in Section 3.2, and the constraint reactions and the deformed shape behave as Sections 3.4 and 4.1 show, but the discretisation error in the reported strain has not been quantified. The local curvature reported in Section 4.3 is obtained from a sampled profile and inherits the same reservation.

5. Conclusion

The progressive die bending process of the stacked in conduit conductor has been analysed in ANSYS Mechanical 2025 R2 over the first two increments of the forming schedule, which carry the conductor to a bending radius of 2.836 m, in advance of the bending test on the prototype conductor.

A three dimensional model of the conductor and the three rotating dies was established. The rigid body motion that arises from the absence of tangential contact stiffness at the start of loading is removed by constraining the lateral displacement of the end faces and the axial displacement of the mid section during the first load step, and the reactions of both constraints remain below 0.4 percent of the die reaction. The contact between the dies and the jacket must be allowed to re-establish its pairing during the rotation, since retaining the initial pairing costs the conductor its lateral restraint.

Circular geometry relates the die stroke to the bending radius. The local indentation of the jacket beneath the die absorbs 0.535 percent of the imposed stroke at the first increment and 0.745 percent at the second, and neglecting it biases the radius by about half a percent.

The outer layer of the tape stack on each side is copper stabilizer rather than coated conductor, so the fibre that governs the strain limit lies at one third of the stack half height and not at its surface. Equation (1) then places the minimum bending radius at 1.256 m for an allowable strain of 0.3 percent, one third smaller than the value obtained when the stack envelope is used.

The deformed shape is not a circular arc. The radius beneath the centre die is 1.412 m at the end of the second increment against the 2.836 m that the three point relation returns, and the curvature is confined to a length comparable with the feed of one rotation. The four rotations that close an increment reduce the peak curvature by 16 percent and widen the curved region from 55 to 80 mm without deepening the bend, and the maximum axial strain of the stack falls by 14 percent over the same load steps. The rotations therefore redistribute the bend as intended, but they recover only part of the concentration, because in three point bending permanent curvature can form only where the moment exceeds the yield moment of the section.

The axial strain computed for the stack exceeds the value that beam kinematics gives at the span radius by a factor of four at the second increment, and by a factor of two when the local radius is used in place of the span radius. A minimum bending radius fixed from the kinematic relation at the target radius of the coil is therefore not conservative, and the strain that governs the tape has to be taken from the curvature reached beneath the die.

Completion of the remaining increments of the forming schedule to the target radius is the immediate continuation. Beyond that, future work comprises the relaxation of the internal interfaces to a frictional state,

for which the interface friction coefficients and the residual radial compression of the jacketing process are required, a mesh sensitivity study, the addition of an unloading step to obtain the springback and the residual radius, the same analysis for bending about the orthogonal axis, and validation against the bending test of the prototype conductor.

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