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SOME CONSIDERATIONS ON THE STRESS ANALYSIS OF THE SWISS COIL FOR THE LARGE COIL TASK

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ABSTRACT

A finite element stress analysis of the coil under consideration is unavoidable due to the proximity of the stresses to the 0.2 % yield strength. The casing of this D-shaped coil is both a hollow body and a looped one. This leads to computing costs and memory requirements which are enormous and preclude any parametric study. To reduce computer costs a newly developed code, FLASH, has been used. It has a hybrid stress model leading to more rapid converge and thick plate elements which allow bending moments to be computed. Only one thick plate is needed across the thickness of the casing and local stress concentrations are obtained from the mean stress and the bending moment. Several models were developed most of which can be set up automatically.

Comparisons between the models and with ASKA finite element results from BROWN BOVERI Co. essentially show agreement. This gives confidence in the models used. Parametric variations were done to study the effects of boundary conditions. These affect the local strass concentrations, which are near the 0.2 % yield strength of the steel contemplated. As the loads are not reversed this should still be acceptable. Such calculations were done at costs of a few percents of conventional finite element calculations. Data preparation could take as little as a quarter of an hour.

The casing of individual conductors has also been investigated with the same code. Both the effect of the Lorentz forces and those arising from the quench pressure due to helium heating on loss of superconductivity have been considered. Strain measurements, with and without epoxy insulation, have since been done by BROWN BOVERI Co. at 4 K. They confirm the calculated values of overall elastic deformation.

1. INTRODUCTION

The Large Coil Task at Oak Ridge National Laboratories will test 6 superconducting coils of a size about half that expected for a Tokamak fusion reactor. Each coil will be made by a different manufacturer or association. The Swiss coil designed by Brown Boveri Company, Oerlikon, uses NbTi conductors and forced cooling by supercritical helium in pressure pipes. The whole is inside a stainless steel casing, fig. 1.

The casing represents a hollow body bent into a complete D-loop. It was decided to do a finite element strass analysis at EIR in parallel to the analysis being performed at BBC with the ASKA programme to provide a comparison. The load case that would be examined would be that thought to be worst - 5 coils at nominal load and the coil next to the test coil switched off. The method to be used should provide results, easy to verify and to understand. It should allow more oversight of the input and be fast in setting up. Finally it should be cheap enough to allow parametric variations. This led to the choice of the programme FLASH, and the use of several simplified models coupled to an auxiliary programme for generating the data automatically. Conditions on the casing of the individual conductors were also examined.

2. THE PROGRAMME FLASH

The programme FLASH [1] uses a hybrid stress model first suggested by Pian [2]. Two independent power series are used, the one for the displacement along the edges of the element, the other for the stresses inside the element. As a consequence there is lack of equilibrium at the edges and the displacement along the edge is inconsistent with the strain within the element. The convergence, number of elements needed, is very rapid. Whereas the kinematic model is too stiff and the equilibrium model too soft, the hybrid model lies in between. The programme has thick plate elements. These compute the bending moments explicitly as well as the usual forces. Thus a single element can be used across the thickness of a wall and the stress distribution can, nevertheless, be computed. This is ideal for the casing.

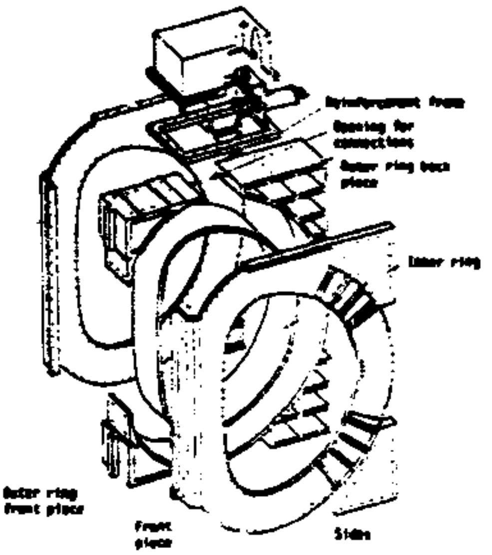

Fig. 1 Assembly of the casing

3. PROBLEMS OF SIMULATION

Plates are not the ideal for simulating the conductor or the insulation cushion between it and the casing. Preliminary tests showed that the forces from the condunctor acted on two sides only of the casing. However, the conductor has some rigidity, more noticeably at the sharp corner, so the Lorentz forces cannot be applied directly to the casing. Test showed the best way of simulating the insulation cushion which takes pressure but no shear. This led to a scheme with plates only. The 4 mesh ponts for the conductor allow the simulation of the "pinch" effect of the Lorentz forces on it, as well as the usual forces on a coil

- radially outwards in the plane due to the nominal flux, plus
- sideways, normal to the plane due to the coil that is off.

The modelling of the conductor is not sufficiently detailed to draw conclusions as to the real state of stress in the many conductors. It does, however, represent a suitable way of loading the casing. Only very few plates are used for the casing around the cross section and this may be too few to simulata the geometry. Hence, the programme was used for obteining the overall stress distribution only and suplemented by detail hand calculations for week points.

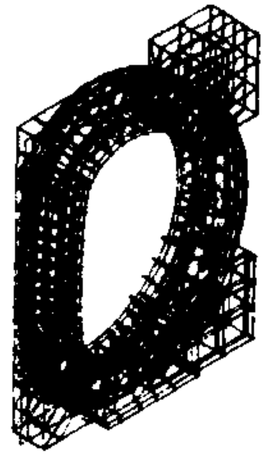

Fig.2. The KLAUSER model

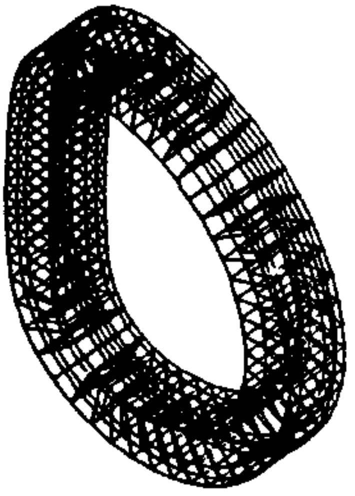

Fig.3. The FULL-SLOOP model

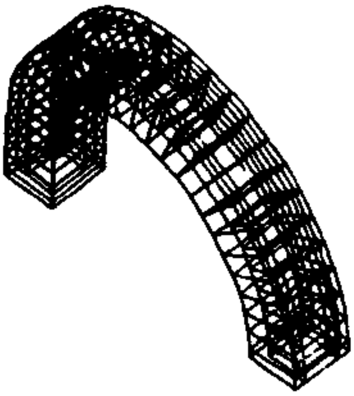

Fig.4. The HALF-SLOOP model

4. THE MODELS

Several models were set up and compared to one another and to that of BBC |3|

- KLAUSER, Fig. 2, which was set up by hand. This proved insoluble as shown and was reduced to a model of the upper half of the coil only by assuming it to be symmetric.
- FULL-SLOOP, fig. 3, which provided the basic information for detail calcutations. This has a simplified cross-section and was set up automatically. Only plate elements were used. They compute the bending moments as well as the stresses.
- HALF-SLOOP, fig. 4, which provided a reasonably cheap model for parametric comparisons. Symmetry is again assumed.

For comparison, two assumptions were investigated for the insulation between conductor and casing. Orthotropic and isotropic elements were used respectively. As the insulator can slide freely, orthotropic properties are more realistic.

5. RESULTS

5.1 Principal stresses in the conductor

The stresses in the conductor are basically hoop stresses. Although little can be deduced about the detail of the stress distribution in the conductor because of its complicated geometry, the hoop stress should be reasonably true for the conductor as a whole. The maximum stresses are compared in table I. They show relatively good agreement both as to value and position of the maximum. These are not critical for the design.

TABLE I

Maximum stresses in the conductor

	Tension MN/m^2	Compression MN/m^2
Klauser	101.8	-121.9
Full-Sloop	93.4	-77
Half-Sloop		
Othotropic insulation	96.7	-77
Isotropic insulation	73.8	-59
ASKA	110	-50

5.2 Principal stresses in the Casing

The D shape of the coil is basically chosen to reduce bending moments in Tokamak type coils. As expected, the principal stresses in the casing are close to pure hoop stresses, (σ circumferential large). They are about 16 % of the yield strength, table II. The three Sloop models show little difference, fig. 5, so that the much cheaper HALF-SLOOP can be used. The differences between SLOOP and KLAUSER models are a little larger in places but for such dissimilar models agreement is excellent. KLAUSER is unrealistically a half loop with isotropic insulation.

5.3 Stress concentrations in the casing

The programme FLASH also gives the bending moment at the mesh point of plate elements. This allows the computation of stress concentrations at the surface. These are caused by the out-of-plane forces leaning on one side of the casing. The design of the casing shows a thinning of the side walls near the bucking post, where the coil is wedge-shaped and space is at a premium. This is also where the programme gives the largest bending moment. Hand calculations show this to be a critical point, the largest moment of 405 KN.m/m occuring at the plane of symmetry near the bucking post. In this respect, the agreement of HALF-SLOOP is not so good, having a value larger by 11 %, table II. This could be due to the proximity to the artifical constraints needed for symmetry. The bending stresses and maximum stress were also calculated at the corner of the key.

TABLE II

Maximum stresses in the casing

	Principal stresses MN/m²	Bending moments KN.m/m
Klauser	185.5	
Full-Sloop	135.2	405
Half-Sloop		
Othotropic insulation	135.3	451
Isotropic insulation	140.5	
ASKA	210	

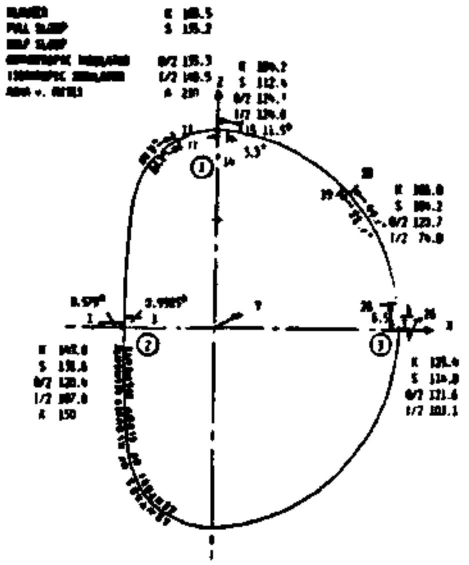

Fig.5.Maximum principal stresses in the casing

① Max. tension in the conductor

Max. principal stress in the casing

② Max. bending moment in the casing

Max. v. Mises comparison stresses

③ Max. stress in the casing with a softer torque ring

6. SENSITIVITY STUDY

6.1 Boundary conditions and their influence on results

The coil is held in postition by two structures

- the bucking part and
- the two torque rings.

The straight part of the D rests against a hexagonal bucking post (restraint in x-direction) which has a key-way to give restraint in the y-direction. The bucking post itself rests on a spider with six legs and six feet. This structure and the bucking post are outside the scope of this study. The post will behave as a beam under the applied load. This has been simplified for the model to a set of simple springs on the relevant nodes, such that the total spring rate is approximately equal to the total spring rate of the Technical Specifications |4|. To test the sensitivity ot this assumption, all spring rates were divided by two. The results are shown in table III. There is little effect in the conductor. The maximum principal stress in the casing, however, increases by 21 % and the maximum bending moment by 2.5 %.

TABLE III

Effect of some parameters

	Maximum principal stress MN/m²		Maximum bending moment in casing
	Conductor	Casing	KN.m/m
Basic Full Sloop	93.4	135.2	405
Half Sloop - Standard	96.7	135.3	451
- halved spring rates at bucking post	104.4	163.8	463
- torque ring spring rate reduced from 3.10^6 to $3.4.10^5$ KN/m	98.2	152.9	483
- model with half number of meshes	96.2	136.5	445

It was not possible to take into account the effect of the coil lifting off the bucking post at the top without extensive iteration. This, however, occurs over a relatively short length and involves relatively small forces.

The two torque rings, top and bottom, restrain the coil from out-of-plane forces. They are constructed to exert only an out-of-plane force (y-force) and some minimal torque around the other two axes. Most of the work described was done with an assumed restraining spring rate of 3.10^6 KN/m per ring per side. It is difficult, however, to obtain such a high stiffness with a ring structure. An analysis of the boundary condition obtained from a simple model fo the complete structure |4| suggests a spring rate of $3.4.10^5$ KN/m as appropriate, an order of magnitude less. With this value, the deflections are then much more like those of the complete model. The maximum tensile stress in the casing changes in position from position 1 to position 3 in fig. 5. The increase of 13 % for the casing is of no consequence. However much more important is the increase of 20 % on the maximum bending moment at position 2 in fig. 5, table III. This has a direct effect on the stress concentration at the minimum cross-section. However, some of this increase can be ascribed to the change from full model to helf model. The increase due only to the spring rate is then about 7 %.

6.2 Influence of Model Parameter

The number of meshes round the half circumference was halved. A model with 15 meshes was used. The peak principal stresses were within 1 % of those obtained with the usual number of meshes, table III. There are thus enough meshes around the loop for convergence. Whether this is also true around a single "plane" has not been ascertained.

7. COST COMPARISON

TABLE IV

Cost comparison (indicative)

	sFr.
KLAUSER	25'000
ASKA	80'000
FULL-SLOOP	4'000
HALF-SLOOP	700

It is very difficult to make precise cost comparisons. As an indication, however, some costs are summarised in table IV. A run for the KLAUSER model or the ASKA programme needs several months data preparation. A parametric change with HALF-SLOOP some quarter of an hour. This is thus a powerful tool as far as clarifying

-the effect of assumtions in boundary condition
-the effect of changes in the model itself
-actual design changes

This increases the value and confidence in a finite element stress analyses.

9. CONDUCTOR CASING

The conductor consists of strands of super-conductor imbedded in copper wires lodged inside a steel casing, fig. 6. The types of steel that come into consideration are AISI 316 L and LN. There are two main loads, that due to the Lorentz forces and that due to the quench pressure. The Lorentz force in the coil produces a maximum pressure of 50 MN/m^2. After the beginning of quenching the magnetic field decays with a time constant of 6.7 sec. At the critical time of t = 2.5 sec., the maximum Lorentz pressure is 34.43 MN/m^2 and the quench pressure of helium inside the casing is 10 MN/m^2. Early tests showed that the corners of the casing had to be reinforced to withstand the Lorentz pressure.

Several cases were computed and are summerized in table V.

Case 1 and 2 considered the casing without conductor and were respectively with and without insulation. The reductions in height, Δh, obtained with a pressure of 50 MN/m^2 were

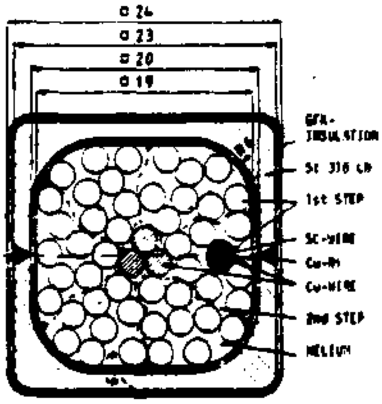

Fig.6. The LCT conductor

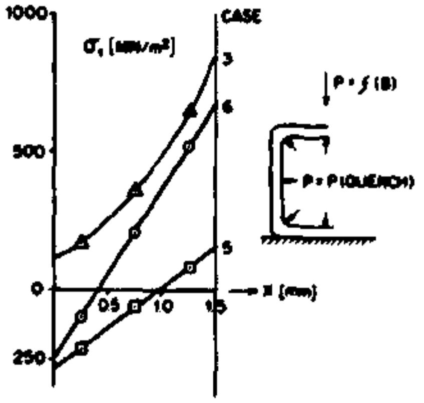

Fig.7. Maximum compressive stress in the conductor casing.

compared to the results of stress tests performed at 4 K. There is satisfactory agreement and this lends credibility to the computing method. All measurements on superconductors were performed at the BBC laboratories in Oerlikon |3|.

Case 3 considers 50 MN/m^2 on the casing with the insulator and the conductor, with no tension allowed on the side walls as is the case when the casing is next to the coil casing.

Case 5 considers the internal quench pressure of 10 MN/m^2 only, for the same conditions.

and Case 6 supersposes both Lorentz (34 MN/m^2) and quench pressure.

The stress distribution is shown for Cases 3, 5 and 6 in fig. 7 at the critical cross-section. Locally the compression due to the Lorentz forces exceeds the yield strength for 316 L (σ 0.2 = 569 MN/m^2) and plastic deformations are expected and observed in the tests. The pressure is still below the ultimate tensile strength and below twice the yield strength so failure will not occur. But this is not an acceptable situation. The safety factor is too small for LCT design requirements. The stresses due to quenching never reach the maximum peak stress so quenching need not be taken into account. With 316 LN, the maximum stresses stay below the yield strength (σ 0.2 = 1143 MN/m^2). Thus 316 LN is an acceptable steel for the conductor casing whereas 316 L is not.

TABLE V

Summaryof results on the conductor casing

Case no.		1	2	3	5	6
Applied pressure	MN/m^2	50	50	50	0	34.43
Quench pressure	MN/m^2	0	0	0	10	10
Max. compression	MN/m^2	675	980	850	200	700
Δh calculated	μ	52	107	94		
Δh measured	μ	65	92.5			

9. ACKNOWLEDGEMENTS

We would like to thank Mr A. Segessemann of BBC, Oerlikon, for many fruitful discussions and for letting us use the results of his computations,|3|.

10. CONCLUSIONS

The various loop models agree sufficiently amongst themselves and with the ASKA results to give confidence in their form and in FLASH. The overall principal stresses in both steel and conductor are nearly pure hoop stresses. Those in the steel are well below the 0.2% yield stress. Local stress concentrations have been calculated by hand and show that the bending moments are much more important than the stresses at the centre of gravity of elements.

A simple model has been evolved which enables quick parametric studies to be made. This shows amonst other things the importance of the boundary conditions which have to be taken from a model of the full structure.

Considerations of the conductor casings show that 316 LN steel is acceptable for the conductor casing, whereas 316 L is not. Steel 316 LN is, however, difficult to machine on such a large scale.

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