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# Evaluation of the Fretting Resistance of the High Voltage Insulation on the ITER Magnet Feeder Busbars

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# Evaluation of the Fretting Resistance of the High Voltage Insulation on the ITER Magnet Feeder Busbars

**N Clayton**[1], **M Crouchen**[2], **D Evans**[1], **C-Y Gung**[1], **M Su**[1], **A Devred**[1] and **R. Piccin**[1]

[1] ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St. Paul Lez Durance Cedex, France,
[2]Rockwood Composites Ltd, 8 Venture Court, Bradley Lane, Newton Abbot, Devon TQ12 1NB, U.K.

David.Evans@iter.org

**Abstract**. The high voltage (HV) insulation on the ITER magnet feeder superconducting busbars and current leads will be prepared from S-glass fabric, pre-impregnated with an epoxy resin, which is interleaved with polyimide film and wrapped onto the components and cured during feeder manufacture. The insulation architecture consists of nine half-lapped layers of glass/Kapton, which is then enveloped in a ground-screen, and two further half-lapped layers of glass pre-preg for mechanical protection. The integrity of the HV insulation is critical in order to inhibit electrical arcs within the feeders. The insulation over the entire length of the HV components (bus bar, current leads and joints) must provide a level of voltage isolation of 30 kV. In operation, the insulation on ITER busbars will be subjected to high mechanical loads, arising from Lorentz forces, and in addition will be subjected to fretting erosion against stainless steel clamps, as the pulsed nature of some magnets results in longitudinal movement of the busbar. This work was aimed at assessing the wear on, and the changes in, the electrical properties of the insulation when subjected to typical ITER operating conditions. High voltage tests demonstrated that the electrical isolation of the insulation was intact after the fretting test.

## 1. Introduction

After installation, the insulated bus bars will be supported by a series of stainless steel supports (clamps). There is a nominal 2 mm radial clearance between the insulated busbar and the clamp, and during machine cool-down the approximately 30 m long bus bars will slide within these clamps by up to 50 mm; the machine design is for 100 cool-downs.

During operation of the ITER device, there will be large Lorentz forces on the bus bars that are reacted through the clamps. Many of the ITER magnets are pulsed and during machine operation the bus bars will slide up to 5 mm during each of the 30,000 lifetime pulses.

To assess the overall effects of the busbar insulation sliding within a close fitting stainless steel clamp, a test assembly and test specimen were devised and manufactured to produce a configuration that closely matched that of an operational insulated bus bar.

The system has to apply a constant load, irrespective of wear on the insulation, since in practice the Lorentz force of up to 15 kN per clamp [1] will ensure that the busbar remains firmly in contact with one surface of the clamps. The test assembly must ensure that the applied load is maintained when the system is cooled to 77 K and remains constant while cycled through ±5mm for up to twice the ITER lifetime of 30,000 cycles.

After cycling in this way, specimens were subjected to high voltage and partial discharge testing to assess the integrity of the insulation.

Test specimens that are used to evaluate the response of the insulation to these demanding conditions must be manufactured using identical materials and process conditions to those used for the feeder busbar. A clamp system that exactly replicates that of the ITER design forms the other component of the test set-up.

## 2. Materials

A stainless steel bar was machined to a diameter of 43 mm and was used as a ‘dummy’ busbar. The insulation was based on a plain weave, S-glass fabric of approximately 0.25 mm thickness pre-impregnated with ~ 40 weight % epoxy resin (Gurit SE84LV) [2] that has been selected, tested and described in more detail by Clayton[3].

Pre-impregnated glass tapes 25 mm wide were combined with 20 mm wide Kapton HN tape [4]. In this development stage of the project, only limited quantities of material were required for testing and therefore manual techniques were used to combine the glass and Kapton tapes; the method of combining these tapes is also described fully in [3].

The 316L stainless steel bar was grit blasted to produce a surface roughness of Ra = 4 microns, detergent cleaned and its cleanliness confirmed using the “water break test’ as described in [5].

## 3. Test Assembly

The principles of the fretting rig are illustrated in Figure 1. The bus-bar clamps are located between two side plates, one clamp is firmly bolted to each side plate and the other clamp floats within guide rails. A pivot pin runs between the side plates, located at the bottom of the assembly to provide a fulcrum for a “loading bar”.

External to the cryostat, a ‘lever arm’ is attached to the loading bar with the required mass at the end of this arm to produce the necessary balancing moment. The distance between the fulcrum and the point on the floating clamp where the force is applied is 50 mm. Since the force required is 15’000 N, the moment required (15’000 x 50) is 750,000 Nmm.

To balance this moment, with a bar length of 1051 mm, a total mass 713.6 N (72.74 kg) is necessary. The mass at the end of the bar, including the hanger for additional weights, is 2.74 kg and therefore an additional 70 kg was required at the end of the lever arm to provide the necessary load on the clamp.

To off-set the effects of a large load on one side of the system, a balancing arm of the same length and with the same added mass is attached to the opposite side.

As wear on the insulation progressed, the angle of the lever arm may change and this can be compensated for by adjustment of a compensation “wedge”. In practice, the wear was not found to be sufficient to warrant any changes in the wedge position.

A shell was added to the bottom of the assembly in Figure 1 to form a dewar to contain the liquid nitrogen (LN2). In this way, the fretting specimen and clamps were immersed in LN2 for the fretting test; however the arrangement allowed the specimen to be readily warmed to room temperature for inspection.

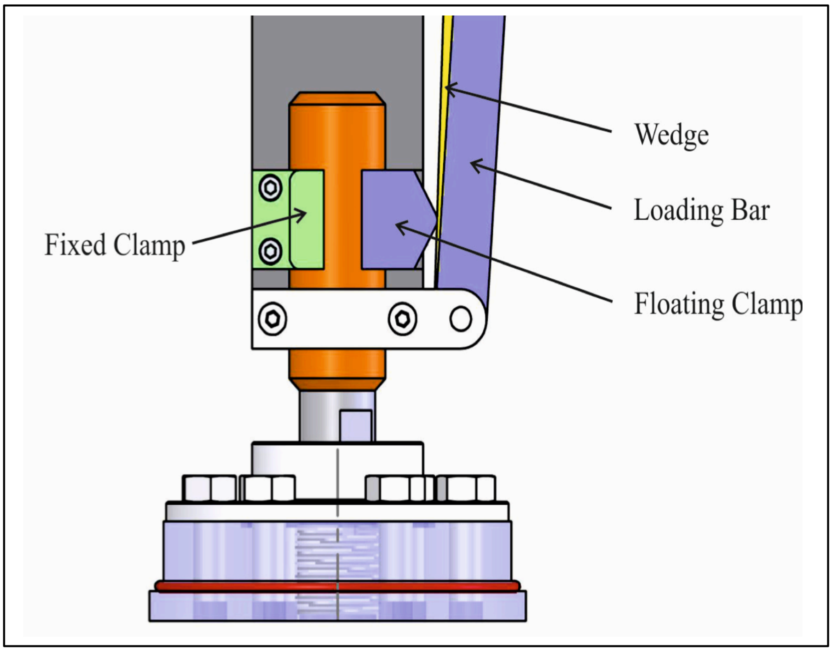


Figure 1. Diagrammatic view of the specimen, clamps and lever arm loading system

## 4. Manufacture of Fretting Specimen and Clamps

A total of 4 fretting specimens were prepared and tested. The first two specimens were identical, and their overall insulation architecture was applied to the stainless steel bar in multiple stages, with a cure between each stage as an aid to minimizing trapped voids and 'wrinkling' of the Kapton tape. A vacuum bag was used to apply compaction pressure on the insulation during cure. The first stage consisted of wrapping one layer of half-lapped (i.e. two thicknesses) of pre-impregnated (pre-preg) glass tape on the steel bar, followed by 4 half-lapped layers of combined glass / Kapton (GK) tape, wound with the Kapton facing outwards. On completion of these layers, the insulation was covered with 'peel ply' and cured. Stage 2 was to apply a further 5 half-lapped glass / Kapton layers, followed by two half-lapped layers of pre-preg, then cure again. The moulding with all the GK layers was typically 5.5 mm thick.

It was found that the use of the vacuum bag led to small wrinkles in the surface of the insulation. In order to avoid these, the last two fretting specimens were cured using trapped silicone rubber to apply the compaction pressure instead of a vacuum bag. This technique is fully described in [3] but in essence uses the high thermal expansion of silicone rubber to apply a compaction pressure to the insulation. The process consisted of wrapping two layers of 3 mm thick, 25 mm wide, extruded silicone rubber tape, trapezoidal in cross-section, around the structure and over-wrapping with five layers of glass tape. When heated to the cure temperature of the pre-preg, the glass tape restrains the expansion of the rubber and so a pressure is applied to the composite insulation.

Specimens #3 and #4 were also built with a ground screen located on top of the GK insulation, but underneath the uppermost two half-lapped layers of pre-preg. The selected ground screen consisted of a nonwoven copper and nickel coated carbon fibre veil [6]. This material is porous to resin, and so can be well bonded into the insulation structure. In order to accommodate the veil, a third manufacturing stage was added which involved wrapping a layer of pre-preg on top of the 9 GK layers, then applying the veil (Figure 2), followed by two half-lapped layers of pre-preg for mechanical protection, and then the final cure.

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Electrical connection to the veil was made using a thin rectangle of copper foil (15 mm by 60 mm), to which a wire had been soldered; the copper foil was laid directly on the veil and overwound by the two half-lapped layers of pre-preg.

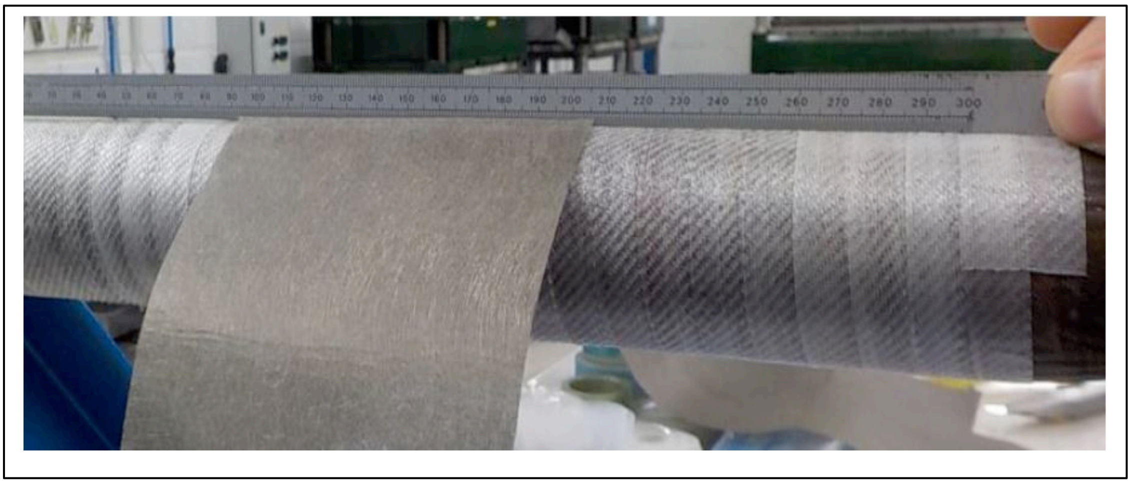

Figure 2 Applying the 'veil' on top of the pre-preg layer

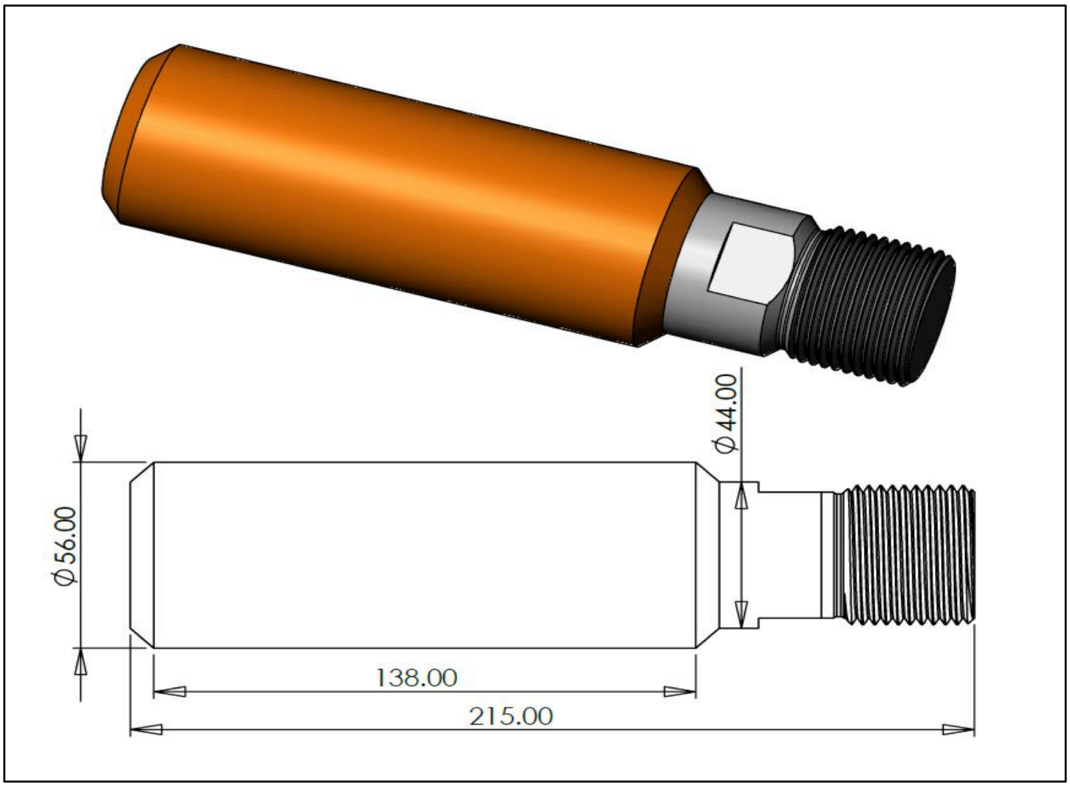


Figure 3. Test specimen machined from the insulated mandrel

The stainless steel bars were 400 mm in length in order to provide a realistic length for wrapping insulation, and from this length, one specimen was machined. The insulation length was machined to

215 mm long, and the threaded portion, for holding the specimen in the test machine, was an M42 x 3 thread, 40 mm in length and 'flats' machined at the opposite end were used for tightening the specimen onto the test machine (Figure 3).

Clamps were machined from 316 L stainless steel, and prepared with a surface roughness of Ra = 1.6 microns. As in the feeders, the clamps were 50 mm long, and were prepared with an R5 radii on their leading and trailing edges. New clamps were used for each fretting test, and the first three fretting specimens were tested with identical clamps. The 4th fretting test employed clamps with an 8 mm wide "flat" region along the centre line, such that the fretting specimen was in contact with this flat along its length. This final clamp design is employed in some locations of the feeder in order to accommodate increased displacements of the busbar.

## 5. Fretting Test Procedures

All mechanical tests were carried out on an Instron, model 8801 by Composite Test & Evaluation Ltd, Honiton, Devon, UK. The bottom of the specimen was fixed to the moving actuator while the clamps were attached to the test assembly, that in turn was connected to the load weighing system.

Initial trials were conducted at a number of frequencies and for practical reasons, 1Hz was selected as the most useable frequency and the amplitude was ±5 mm about a zero point.

A thermocouple was used to ensure that the friction did not cause the specimen to warm up in the LN2 dewar. The diameter of the test specimen was measured in a number of positions around the circumference at room temperature using a hand held micrometer and the mean value calculated. Measurements were made at a height on the specimen that corresponded to a position at the centre point of the clamps. The fretting test procedure was to perform a number of fretting cycles on the specimen at 77 K, and then warm it up to inspect and measure any wear on the insulation. The specimen was then re-cooled to 77 K, and the fretting test continued. The first specimen was inspected and measured after 500, 1000, 5000, 10000 cycles, and then every 10000 cycles up to 60000 cycles. The subsequent specimens were inspected less regularly, but at each inspection it was noted that the test assembly and specimen were coated with a fine black dust.

Each specimen took around 3 full days to test.

## 6. Results

Results are considered under three separate headings:

(a) Wear on insulation
(b) Electrical Characteristics
(c) Calculation of Friction Factor

### *6.1 Wear on Insulation*

The central result from this study is that the specimens suffered wear to the insulation underneath the clamps, but did not lose their overall mechanical integrity. Figure 4 shows the wear on the insulation as a function of fretting cycle, measured for the 4 specimens. As shown in Figure 1, the test set-up incorporates two clamps, and so there are two wear zones on each specimen. The data in Figure 4 shows the average of these two wear zones, and as such corresponds to an average radial wear.

Initially, all 4 specimens displayed accelerated rates of wear, which then stabilised after a few thousand cycles. This may have been due to any outstanding features on the insulation surface, such as small irregularities, being ground away early on in the test. It is interesting to note that Specimens #1 and #2 display significantly different rates of wear despite being ostensibly identical. Figure 5 shows Specimen #2 and its moveable clamp at the end of the fretting test, and a significant ridge can be seen in the insulation that extended into the wear zone. It is postulated that this ridge acted as a stress concentration region and resulted in additional dust formation that accelerated the wear on this specimen compared Specimen #1, which did not have such a prominent feature.

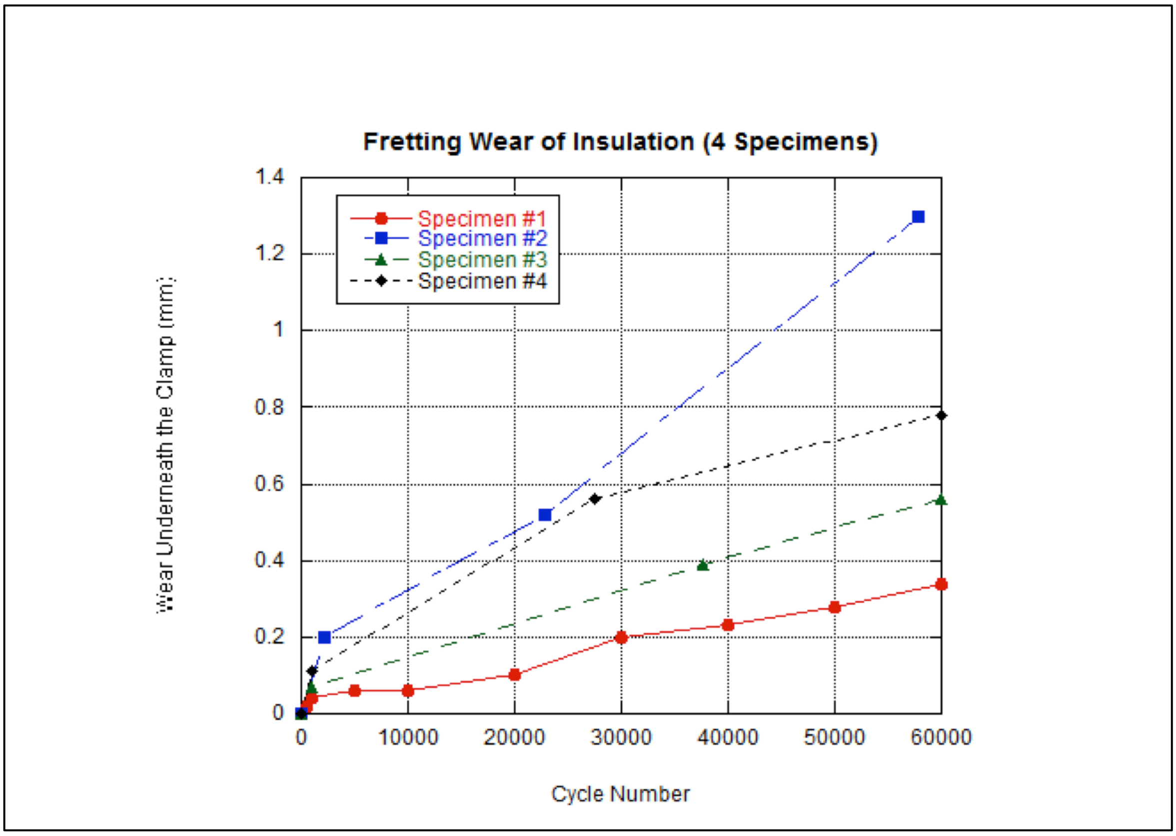


Figure 4. Average radial wear on the insulation as function of fretting cycle number (all 4 specimens)

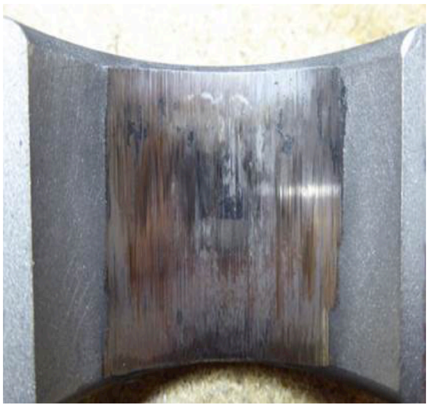

Figure 5. (Left) Photograph of Specimen #2 after the fretting test had been completed, showing a significant ridge in the insulation around the wear zone. (Right) Photograph of the moveable clamp after the fretting cycles showing the polishing action on the contact surface.

*6.2 Electrical Characteristics*

Two specimens (#3 and #4) were evaluated after mechanical testing to examine their electrical characteristics and confirm (or otherwise) that they still met the ITER requirements. These specimens were fitted with integrated ground-screens which facilitated these tests. The insulation resistance was measured between the steel thread and the veil ground-screen using a Megger, model MIT 1525 at 1 kV DC for 1 minute. The insulation resistance of specimen #3 was found to be 2 x $10^9$ Ohms (2 TΩ) and specimen #4 was found to be 1.8 x $10^9$ Ohms (1.8 TΩ), significantly exceeding the ITER requirements.

The specimen geometry did not permit a breakdown test to be performed due to the proximity of the edges of the ground-screen to the high voltage potential on the specimen, which resulted in surfaces discharges. Partial discharge measurements were made to characterise the insulation, which were limited to 10 kVrms for a period of 30 minutes. The partial discharge measurements showed large surface discharges (>2 nC) which masked the signal generated by internal voids. Nonetheless, the partial discharge signal did not increase over the duration of the test, indicating that the electrical performance of the insulation was maintained.

*6.3 Calculation of Coefficient of Friction*

The experiment permitted a rough estimate of the dynamic coefficient of friction to be made. With reference to Figure 6, the coefficient of friction is defined as μ = Ff/Fn, where μ is coefficient of friction, Ff is frictional force, and Fn is normal force. In the experimental set-up, the specimen is fretted against two clamps, each applying 15 kN of normal force, and the friction force is measured directly by the Instron testing machine. Given that the profile of the clamps is identical, it is assumed that the friction from each one is the same; therefore the coefficient of friction underneath one clamp may be estimated by considering half the measured frictional force.

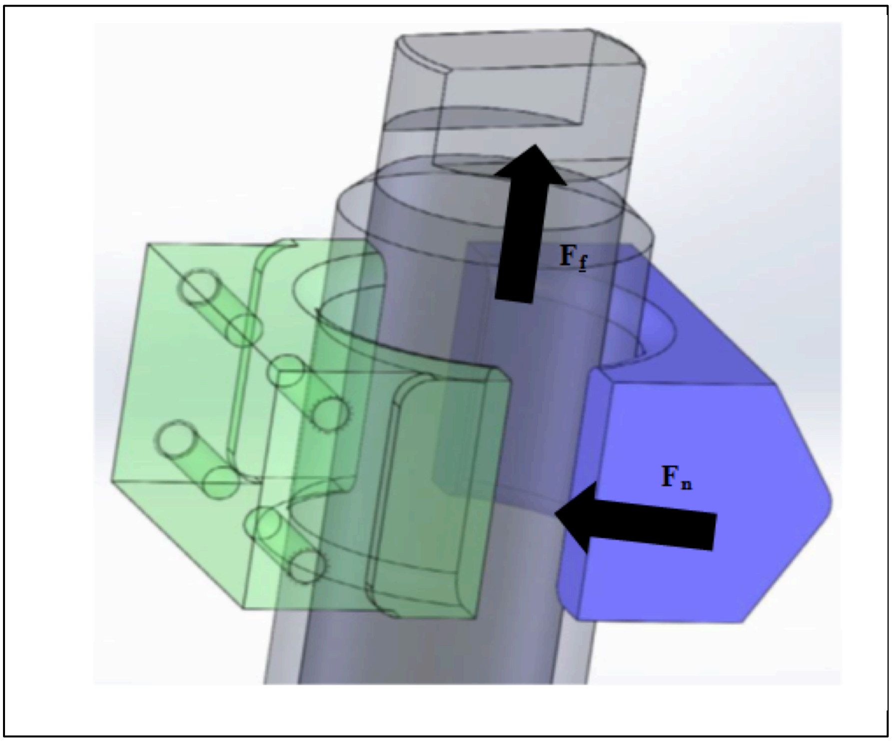


Figure 6. Representation of Friction Force (Ff) and Normal Force (Fn)

It was found that the test results from all four specimens could not be readily interpreted. Careful tests showed that the up and down forces in a fretting cycle were not symmetric, which might be caused by the presence of a residual force as the specimen direction reverses. This indicates that this experimental set-up cannot be used to reliably determine the friction factor. Nonetheless, as an approximation, a friction factor in the range of 0.2~0.4 was deduced.

## 7. Conclusions

A series of fretting tests has been performed on insulation specimens representing the high voltage insulation on the ITER feeder busbars. It was found that the specimens suffered wear to the insulation underneath the clamps, but did not lose their overall mechanical integrity. The amount of wear varied between the specimens, and in all but one was confined to the 'capping' layers of pre-preg which are designed to protect the ground-screen.

The reason for the increased wear on the 4th specimen may be the presence of a crease in the surface of the insulation which led to a concentration of the load in this region.

Electrical tests on two of the specimens fitted with integrated ground-screens revealed that the high voltage insulation was intact electrically after the fretting test. It can be concluded that as long as significant ridges in the insulation are avoided, wear due to fretting can be confined to the pre-preg capping layers whilst maintaining the integrity of the underlying high voltage insulation.

The friction force generated during low temperature cycling has been used to derive an approximation for the coefficient of friction in the range of 0.2~0.4.

## 8. Disclaimer

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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