A multiphysics model to ensure power cables are restrained safely during short circuit fault

M S Yeoman PhD[1], R Damodharan[1], R J Varley[1], L Frizzell[2]
1. Continuum Blue Limited, One Caspian Point, Caspian Way, CF10 4DQ, United Kingdom
2. CMP Products Limited, 36 Nelson Way, Nelson Park East, Cramlington, NE23 1WH, United Kingdom

Introduction

Cable cleats are products designed to ensure the retention and support of cables and conductors in large electrical installations. In addition to their supportive role, they also ensure the protection of the cable terminations, and more importantly are designed to withstand high electromechanical forces in the event of a short-circuit fault, whilst maintaining the integrity of the cables without causing damage.

Although circuit breakers are installed in electrical installations to provide protection, a typical circuit breaker interrupts the fault after three cycles and thus cannot open to suspend the fault. Whilst this may protect equipment, the cables can be damaged within this short period, and depending on the short-circuit fault, may need to be replaced. The replacement of cables comes at a high price, as this not only includes the cost of the cables, but the labour and time in decommissioning and reinstallation, as well as the system downtime.

Numerous cable cleats are available with different design features, advantages and disadvantages. Standards such as IEC 61914:2015[1] and EN 50368:2003[2] specify the requirements, and tests for cable cleats and intermediate restraints used for securing cables in large electrical installations. These standards are guidelines and are not obligatory. Thus, cleat producers do not necessarily need to adhere to them, and if they do, they do not need to do independent third party tests, as these can be done through self-certification. For any electrical installation to be considered safe, power cables need to be restrained to withstand the electromechanical forces generated during a short-circuit, or fault condition. By allowing self-certification and non-adherence to these standards, potentially dangerous designs are made available in the market.

Trefoil Cleat Design

Trefoil cleats are specially designed cleats used to hold three single core power cables in a triangular touching (trefoil) formation, along the length of the laid cables. The basic design features of a trefoil cleat include a base, which is typically attached to a cable ladder, tray, channel, or masonry, and a constraining system to tighten, and fix the three single phase cables in place. Figure 1 below, presents two trefoil cleat designs and some in use.

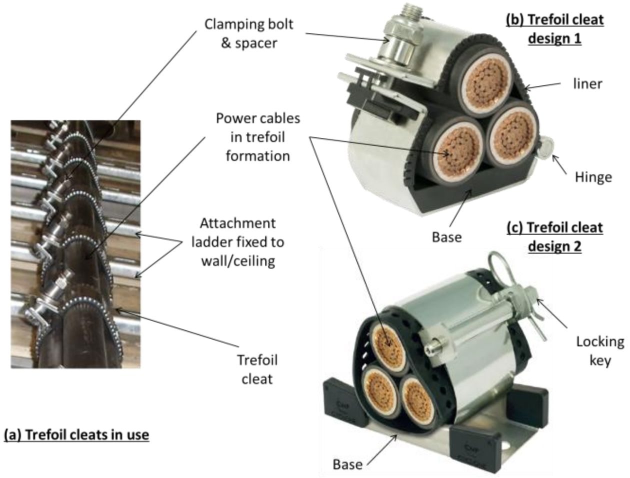


Figure 1: Trefoil cleats in use and variations in design

In order to assess various designs equally, as well as help reduce the development times of trefoil cleats, a transient multiphysics model, including currents, induced electromagnetic forces, material and contact stresses, was developed to fully describe, and simulate the dynamic load conditions on the cables and cleat during a single short-circuit test. The test parameters from the simulation were then replicated in physical tests at an independent test laboratory and the numerical results compared and validated against these physical tests.

IEC 61914 and Trefoil Cleat Tests

IEC 61914:2015 and EN 50368:2003 standards provide details on the testing and certification of cleats to withstand, one (Category 1), or more (Category 2) short-circuit tests. IEC 61914:2015 also provide formulae to calculate the theoretical forces that may be generated in the event of a short-circuit, where, for a three phase short-circuit with cables in a trefoil configuration, the maximum theoretical force on the conductor is given by:

$$F_t = \frac{0.17 \times i_p^2}{S} \qquad (1)$$

where;

F_t maximum force per unit length on the cable conductor in trefoil configuration (N/m);

i_p peak short-circuit current (kA);

S centre to centre distance between neighbouring conductors

In order to verify compliance with the latest standard, manufacturers of cleats, are required to physically test their designs. IEC 61914:2015 provides a method for cable cleats to be short-circuit tested so that the results from different cleat manufacturers can be compared directly.

The typical trefoil cleat test setup is illustrated in Figure 2, where one end is connected to a three phase supply and the other end is connected to a short-circuiting busbar, with all three-phases connected. The cables are required to be restrained and fixed to the test mounting at a minimum of 5 equally spaced points along its length and the cleats are mounted to an appropriately selected cable ladder. The duration of the three phase short-circuit test is required to be no less than 0.1seconds.

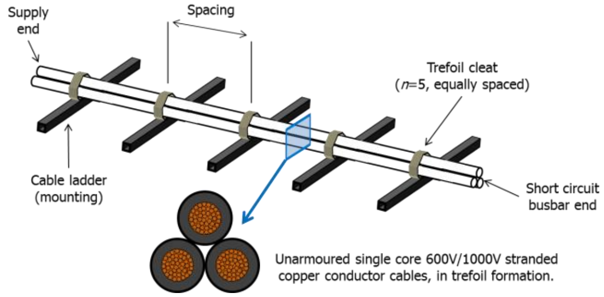


Figure 2: Typical test setup for trefoil cleats without intermediate restraints (adapted from IEC 61914:2015)

When comparing short-circuit test results for trefoil cleats, the fault level, cleat spacing and cable diameter must be known and recorded. Thus, a cable cleat can only be short-circuit rated to withstand a specific peak current, at a given cleat spacing and cable diameter. This leaves the selection of cleats for alternative loads and cable diameters open to interpretation, based on available test data.

In order for a cleat to pass a category 1 (single) or category 2 (multiple) short circuit test at a particular fault level, there should be no failure that will affect the intended function of holding the cables in place. In addition, the cable cleats and intermediate restraints (if used), should remain intact with no missing parts, however minor deformation is acceptable. Finally, there should be no visible damage to the outer sheath of the cable due to the cleats, or intermediate restraints.

Cleat selection

The correct selection of cable cleats is important. Once the maximum theoretical force has been calculated using Equation (1), the current selection process is done by using the test specific current rating and spacing of a cleat design, as provided by the manufacturer, and rearranging Equation (1) to make S (centre to centre distance between neighbouring conductors, or cable diameter) the subject of the formula. In addition, by making use of the maximum rated force per unit length of cleat design ($F^R{}_t$), and the rated cleat spacing (d^R), one can take the cleat spacing (d) for a specific application into account. Thus, cleat design and size selection is possible based on limited physical test data, or worse a single test result. This method of cleat selection is not ideal, as it makes gross assumptions that Equation (1) is proportional across cleat designs, sizes, and spacing along the cable. This can be true for small variations in current, size and spacing from the cleat's rated value, however, this is not the case for large variations. In addition to this, as the cleat's short-circuit ratings are potentially self-certified by the manufacturer, the rated values may not be true. This opens up the possibility that a number of cleat designs currently in use may be open to failure at lower peak loads than specified. Thus, a better selection tool is required to provide engineers the necessary information to ensure that the cleat design selected is strong enough for the specific application, which does not rely on the self-certified ratings provided by the manufacturers.

Multiphysics model

To overcome the issues in the cleat selection process, a three-dimensional transient multiphysics model was developed to test cleat designs. Figure 3 below presents a sectioned view of the model geometry for cleat design 1, highlighting the main components modelled. As can be seen, all the components of the cleat are implemented, including the cables, ladder and attachment means to the ladder, as variations in the way the cleat is attached to the ladder can greatly change performance.

The model is fully parameterised, across a range of cleat types[4] and sizes, where peak fault current, cable diameter, conductor size and type, insulation thickness, cleat and liner material properties, as well as spacing and cable type, can easily be adjusted and assessed within the model.

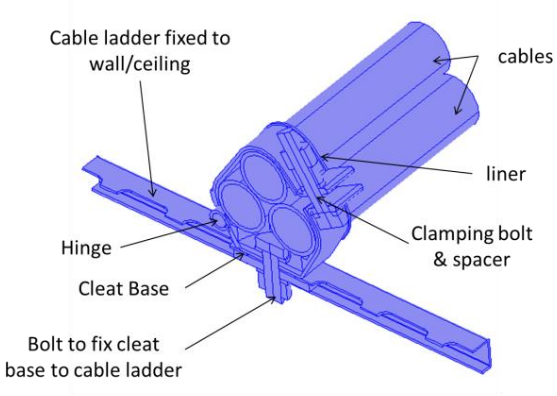


Figure 3: Sectional view through trefoil cleat model (design 1), showing the various components modelled.

The model includes electrical currents and magnetic field physics which are coupled to the structural mechanics of the cleat design, and are used to fully describe and simulate the dynamic electromagnetic load conditions on the cables and cleats during a short-circuit fault. To ensure that the model correctly simulates reality, material plasticity, and hyper-elastic material models for rubber-like materials were implemented. Material plasticity models were used to model the copper cable cores, the metal cleat components and the ladder. Additionally, full contact was modelled between the cable sheaths and the trefoil cleat, and the components of the cleat and attachments to the ladder. The contact models used Coulomb friction with the appropriate coefficients of friction applied across the various contact surfaces. Material properties were obtained from supplier test data where available, or from Cambridge Engineering Selector (CES 2017)[3]. The materials and material models implemented in the model for the various components are presented in Table 1 below.

Table 1: Materials and material models implemented

Material	Material Model	Model Components
Copper alloy	Elasto-plastic	Cable core
HDPE	Elasto-plastic	Cable sheaths
Stainless steel 316L	Elasto-plastic	Cleat parts
Proprietary polymer	Hyper-elastic	Cleat liners, cleat & booster
Galvanised steel	Elasto-plastic	Cable ladder & channels

In order to reduce computational expense, the model made use of the repetitive nature of the system, where only a single cleat was modelled; the central cleat as illustrated in Figure 2, and a length of cable on either side of the cleat. The model made use of symmetry and periodic planes, where applicable. Additionally, only a section of the cable ladder was modelled, where the ends of the ladder were fully constrained.

Results

The model was used to assess various different cleat designs[4-5], however only the results of one of the cleat designs (design 1) are presented, with the following configuration:

- Cleat type: Design 1
- Cleat Configuration: 33-38
- Cable diameter: 36 mm
- Cable Core CSA: 500 mm^2
- Cleat spacing: 300 mm
- Peak fault current: 190 kA

.

The model took over 18 hours to run to a simulated short-circuit time of 0.1s on a desktop PC with two Intel® Xeon® 3.10GHz processors and 24GB of RAM.

Figure 4 below gives example output plots from the model at specific times during the short circuit test, including, (a) displacement magnitude, (b) von Mises stresses on the cleat, and (c) electromagnetic force vectors acting on the conductors (N) and magnetic field lines. The figure illustrates how the displacements, stresses, electromagnetic field and forces vary with time.

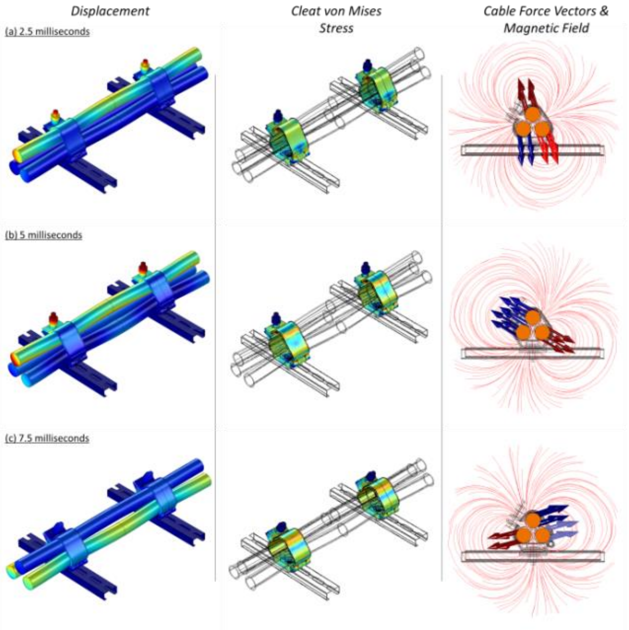


Figure 4: Cable displacements, von Mises stresses, force vectors & magnetic field at various time points during short-circuit test.

Figure 5 below, presents the von Mises stresses over time at four specific points on the cleat during the first 20 milliseconds. Points 1 to 3 can be seen to go above the material's yield stress at 2 milliseconds, but remain below the material's Ultimate Tensile Strength (UTS), thus permanent plastic deformation is expected to be observed at these points on the cleat following the test, but no material failure.

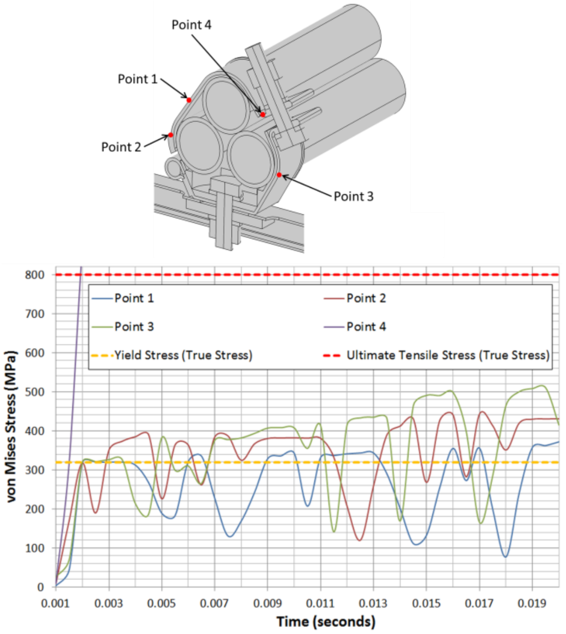


Figure 5: Analysis of stress levels at four points on cleat vs. material yield and UTS values

However Point 4, which lies on the upper surface of an elbow bend on the cleat wall, does go above the UTS. Thus, material failure is expected. However, this material failure is only observed to occur locally on the surface and is superficial, thus catastrophic cleat failure does not occur. In order to better visualise the regions where superficial failure occurs, and to identify regions where cleat design features could be improved, threshold plots of where the cleat goes above the material UTS are provided and presented in Figure 6 below.

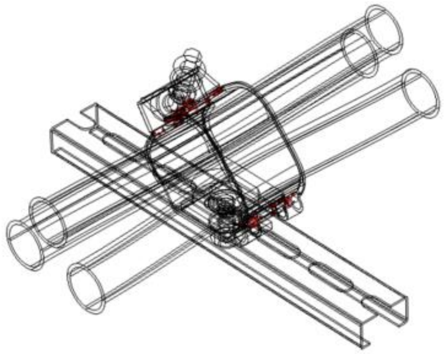


Figure 6: Regions where cleat stresses go above the UTS

From Figure 6, the main regions where material failure occur on cleat design 1, are at the sharp corners near the cleat hinge, and on the surfaces around the two elbow bends, where the restraining bolt is placed. In addition to this, the region around the clamping bolt hole are also observed to go above the UTS. However, the material failure is superficial and very localised around these sharp features and bends, and does not cause complete cleat failure or loss of functional integrity, during the short-circuit fault.

A Factor of Safety (FOS) plot relative to the UTS of the material is presented in Figure 7 below, and defined as follows.

$$FOS = \frac{UTS}{Material\ stress\ level} \qquad (2)$$

The FOS plot provides a quick visual guide of design hot spots and regions where the cleat is close to failure, where FOS values below 1 present material failure, and values close to, but above 1, are close to material failure.

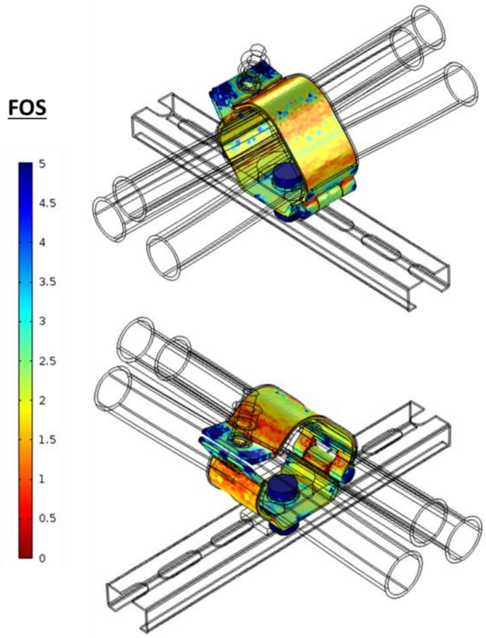


Figure 7: Factor of Safety (FOS) relative to material UTS

Thus, for a short-circuit rating of 190kA, the regions close to failure in cleat design 1 are at the bends in the cleat wall, and around the sharp corners of the hinge, as shown by the red regions in the images in Figure 7.

Figure 8 graphically presents the radial displacements observed over time at the mid-plane between the cable cleats for each of the three cables in trefoil formation. Cable 1, which is at the apex of the trefoil formation and furthest away from cleat base and ladder, radially displaces the most, with a maximum value of 21.46mm. While, the maximum radial displacements observed on cables 2 and 3 were found to be 11.09 and 12.06mm, respectively. The reason the radial displacement in cable 1 is much greater than the other two is due to its position at the apex of the trefoil formation. At this point, the cable does not have the same support, as the other two cables, which lie on the cleat base and are supported by the ladder.

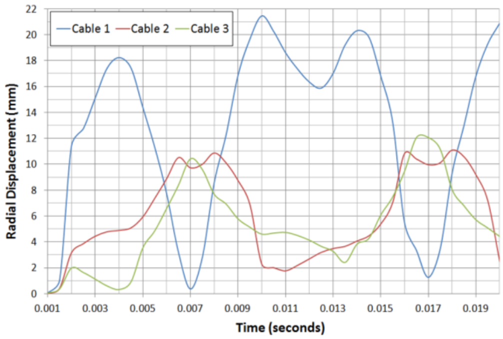
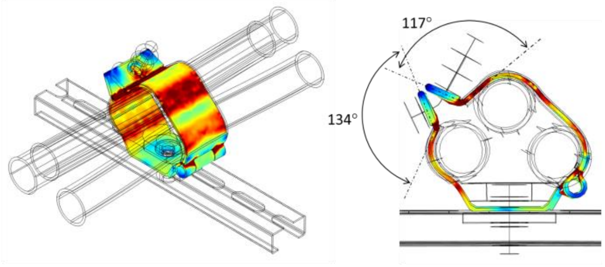


Figure 8: Radial displacement of cables centers between adjacent cleats over short-circuit fault

Figure 10 presents the final deformed state and the residual stresses of the cleat following the short-circuit test. From the side view of the cleat (Figure 10c) and comparing this to the initial un-deformed state (Figure 10d), the initial 86° and 100° elbow bends in the cleat wall are opened to larger angles of 134° and 117°, respectively. In addition, the residual stresses can be seen to be highest at these deformed bends and sections of the wall, as illustrated by the dark red regions in Figure 10.

(a) Isometric View 1

(c) Side View



(b) Isometric View 2

(d) Initial Undeformed State

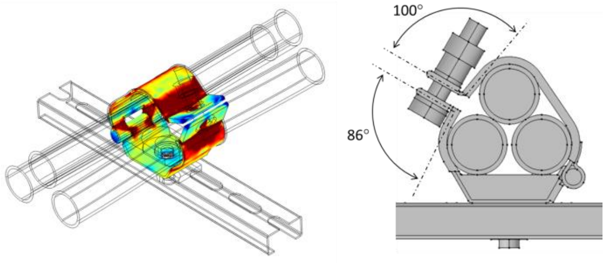


Figure 10: Residual stresses and final deformation, following short-circuit simulation

From the figures presented above, a wealth of information on the cleat's status during and after the short-circuit test is available. From this data an engineer can make a well informed decision on the cleats ability to withstand a particular short-circuit load at a specific spacing, using a particular cable and method of attachment.

In addition to the plots presented above, the cable force per unit length values obtained for each cable during the short-circuit fault were found to vary between 3.1 kN/m and 124.5 kN/m, and were found to decrease gradually over time. The peak forces over time where found to be in phase with the three phase current applied to each cable.

Comparisons to Physical Tests

The multiphysics model results were compared and validated against physical tests for ten different cleat designs, materials, attachment, and short-circuit loads. Cleat designs, included the two presented in Figure 1, as well as five other trefoil cleat designs [4-5]. In this section, we only present the comparisons to that of cleat design 1, and the test configuration presented above.

Physical testing of each trefoil cleat design was performed at an short-circuit testing laboratory, where all tests were witnessed by an independent 3rd party. High speed video footage and images were captured before, during and after testing. In addition to this, electrical inputs to the cable from the supply end were monitored.

Figure 11 below, presents the comparisons between the model cleat stresses and displacements at various time points (2.5, 5 and 7.5 milliseconds), compared to the high speed video footage obtained during the physical tests. The displacements and deformed state of the cables and cleats closely follow those observed in the physical tests. Figure 12, presents the cleats final deformed state and residual stresses, versus the physically tested cleat. Again very close correlations are observed between the model and physical tests. In addition, it can be seen from this figure that the bolt is permanently bent, as observed in the model. From these two figures and the additional information collected, the model gives good correlations to the physical tests, under the defined load current and spacing. Additionally, the model predicted that the integrity of the cleat under the short-circuit load would remain intact, as was observed in the physical tests.

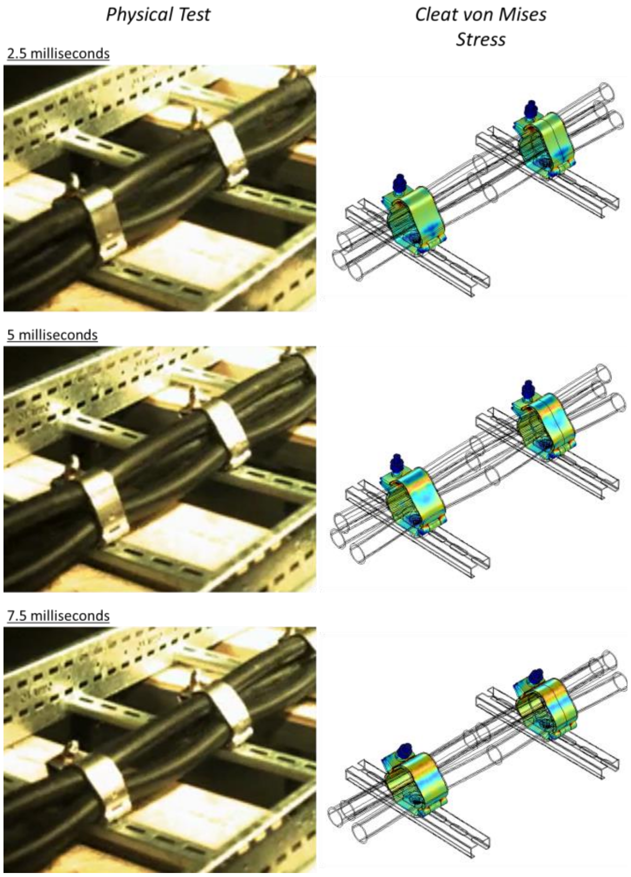


Figure 11: Comparison physical test data vs. model solutions at various time points during short-circuit testing

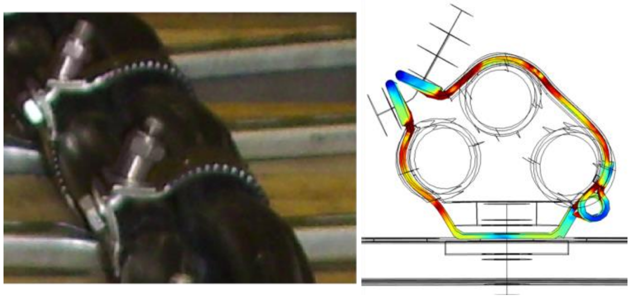


Figure 12: Comparison of cleat deformation following physical test vs. model.

As described earlier and illustrated in Figures 5 and 6, the model predicts that superficial regions of the cleat surface do go above the material's UTS, as observed at point 4. This phenomena and the expected surface failure were indeed observed in the physical tests, as illustrated in Figure 13 below.

The good correlations made between the model and physical tests for cleat design 1, were also observed for the other nine cleat types and configurations tested. The model correlations and deformed states during and following testing, give confidence in the validity of the models capability to predict a cleats response, over a range of designs, sizes, spacing, currents and attachment means.

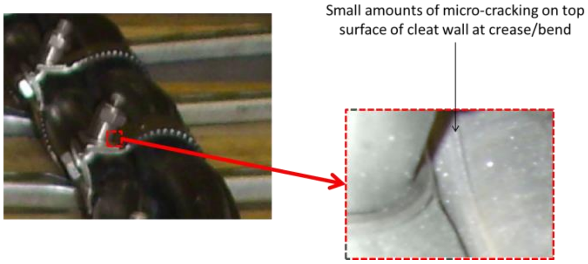


Figure 13: Superficial micro-cracking observed on cleat surfaces following physical testing, as predicted by model.

Comparison to Analytical Solution

Using Equation (1) and substituting the various parameters for the test configuration above, one is able to obtain the maximum theoretical force per unit length expected between the cables. We can compare this to the solutions obtained from the multiphysics model. Table 2 presents the solution obtained from Equation (1) and two model results, one which assesses the electromagnetic forces constrained within the width of the cleat body only, and the other, which presents the average electromagnetic forces along the complete length of cable, including taking into account the deformed cables between the adjacent cleats.

Table 2: Model vs. analytical solution

Analytical (IEC 61914)	Multiphysics Model	
Parameters: *S* = 36mm & i_p = 190kA	Cable section constrained within width of cleat body only	Along complete length of cable, including cable region between cleats
170.5 kN/m	159.3 kN/m	124.5 kN/m
Percentage Variation	-6.53%	-26.98%

As can be seen in Table 2 above, good agreement is seen between the model and the analytical solution for the cable sections constrained within the width of the cleat body only, where the model predicts 159.3 kN/m, 6.53% lower than the 170.5 kN/m value obtained from Equation (1). This was expected, as the model takes into account the radial movements of the cable within the cleat body, resulting in a reduction in the electromagnetic forces as the cables are forced apart.

If one assesses the overall electromagnetic forces on the complete length of cable between the cleats and the cleat body, including the radially unconstrained cable sections between adjacent cleats, one observes a much lower maximum force per unit length value of 124.5 kN/m, as presented in the third column in Table 2; this is due to the fact that the forces acting upon the cables decrease, as the cables are forced further apart during the short-circuit test.

Conclusions

A full transient three-dimensional multiphysics model has been developed to assess trefoil cleat designs and their installations during short-circuit faults. The model is fully parameterised and couples the electrical, magnetic and structural physics to fully describe the response of the cleat, cables, ladder attachment and ladder.

The model has been compared and validated against a range of physical test data, including variations in cleat design, size, spacing and short-circuit current loads. In addition, the models maximum force per unit length observed by the short-circuiting cables has been assessed and compared to the analytical solutions obtained from Equation (1) and IEC 61914:2015, where the model predicts marginally lower maximum forces (6.53% lower for the cleat configuration above as presented in Table 2). This is expected as the multiphysics model takes into account the movements of the cables within the cleat body, and the resulting reduction in the electromagnetic forces.

The multiphysics model gives the user the advantage of being able to understand how a trefoil cleat design and installation configuration will perform under various load conditions, as well as provide data such as residual stresses within the cleat following a short-circuit fault, or multiple short-circuit faults. This will help engineers make better material choices, and design decisions, and highlight design drawbacks, potential flaws, or installation issues, quickly and cost effectively. The model can also help cleat manufacturers ensure that their designs pass test levels and ensure compliance, prior to costly physical tests. In addition, the model can help buyers, who are required to assess various restraining options available on the market, to easily evaluate and directly compare one design to another, for a particular application, ensuring the required safety levels are maintained.

Additional work still needs to be done on the model, including the implementation of the intermediate straps, adding more cable options, including armoured cables, or variations in sheath materials. However, more importantly, the addition of thermal effects on the system due to the joule heating effect of the cable over long short-circuit faults (up to 1second) would be beneficial, as this would affect the material properties and characteristics, and thus the system response. Especially in the case of the cable sheaths, and polymeric materials, where temperatures will easily go above 80°C, resulting in the loss of mechanical integrity and possible power core exposure along the cable length.

Nomenclature

F_t	Maximum force on the cable conductor in trefoil configuration (N/m)
i_p	Peak short-circuit current (kA)
S	Centre to centre distance between neighboring conductors, or cable diameter in trefoil cable configurations (m)
d	Cleat spacing along cable length
${F^R}_t$	Rated maximum force on the cable conductor in trefoil configuration (N/m): $F_t^R = \frac{0.17 \times {i^R}_p{}^2}{S^R}$
${i^R}_p$	Rated peak short-circuit current (kA) for specific configuration, physically tested & passed.
S^R	Rated centre to centre distance between neighboring conductors, or cable diameter in trefoil cable configurations (m) for specific configuration, physically tested & passed.
d^R	Cleat spacing along cable length, for specific configuration, physically tested & passed.
UTS	Ultimate Tensile Strength (Pa)
FOS	Factor of safety, relative to UTS
CSA	Cross-sectional area

References

[1] EN 50368:2003 Cable Cleats For Electrical Installations
[2] IEC 61914:2015 Cable Cleats & Short-Circuit Calculations
[3] Cambridge Engineering Selector (CES 2017), Granta Design Ltd. www.grantadesign.com
[4] www.cmp-products.com
[5] www.cleatselector.com