A modification of the Norris failure criterion for the prediction of the mechanical failure of the aged paper insulation in the windings of a power transformer

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***Abstract*- The deterioration of the insulation in the windings of power transformers affects their lifespan. A commercial insulated Continuously Transposed Conductor (CTC) was studied experimentally, numerically and analytically. The purpose was to understand the mechanisms governing the mechanical failure of the insulating paper, and to achieve a criterion for predicting failure under different conditions. Samples of that insulated CTC were extracted from a coil and aged at 150 °C for different durations inside vessels filled with naphthenic oil. Then the degree of polymerisation and tensile, compressive and shear mechanical properties of the insulation were measured/estimated. Aged insulated CTC samples were subjected to three-point bending tests, producing deformations compatible with a short circuit, and the fractures in the insulation were analysed. The bending test over a CTC sample was simulated by means of a FEM Program. The Norris failure model, applicable to a lamina, was adapted to the studied insulation materials. The predictions of that failure criterion agreed with experimental observations.**

I. Introduction

Their satisfactory dielectric, thermal and mechanical properties make paper and board the most typical materials used as solid insulation in power transformers. The solid insulation is immersed in an insulating liquid, which enhances the dielectric insulation and the heat dissipation. The dielectric, chemical and mechanical properties of the paper insulation decay during the operating life of a transformer because of thermal ageing. Typically, the mechanical properties deteriorate faster than the dielectric ones, and the mechanical failure of the paper caused by the stresses and strains produced by electromagnetic forces is the predominant reason for the insulation-related faults in power transformers [1]. The mechanical breakage of the aged paper can also be the reason for a subsequent electrical breakdown.

It is complicated to apply the pre-existing mechanical failure models for generic cellulosic materials to the insulation of a transformer, as they are extremely theoretical and rest on many ideal hypotheses [2]. Furthermore, it would be essential to include some particular features in those models, for instance: the impact of the dielectric oil-impregnation, the deterioration of mechanical properties due to ageing, the material geometry and realistic mechanical solicitations. The purpose of this study is to develop a criterion capable of anticipating the mechanical failure of the paper insulation after different periods of operation of the power transformer.

II. Materials and Methods

2.1 Experimental methods

A. Thermal ageing and bending tests over CTC samples

The mechanical response of a commercial CTC of a core-type transformer is studied, see Fig. 1 (a). The CTC is wrapped in four layers of thin paper insulation: the two internal ones are made of plain Kraft paper, and the external ones of crepe paper. Test pieces were extracted from the CTC, see Fig. 1 (b), in which the main directions of the insulation (the machine direction (MD) and the cross-direction (CD)) are indicated. The insulation properties, given by the manufacturer, are listed in TABLE I.

Different durations were applied for the thermal ageing of the insulated CTC samples immersed in naphthenic dielectric oil and introduced into temperature-controlled ovens, see Fig. 2 (a): State 0 (non-aged material), State I (aged at 150 ºC for 1 week), State II (150 ºC for 4 weeks) and State III (150 ºC for 9 weeks). After ageing, the average viscometric degree of polymerisation (DP) of both types of insulation was measured according to [3].

TABLE I
Manufacturing Properties of the Studied Insulation Materials

PROPERTY	UNIT	TEST METHOD	Kraft paper	Crepe paper
Nominal Grammage	g/m^2	ISO 536	62.0	80.0
Nominal Thickness	µm	ISO 543	82	80
Nominal Density	kg/m^3	ISO 543	760	1000
Tensile Strength in MD	MPa	ISO 1924	≥ 93.5	≥ 87.5
Tensile Strength in CD	MPa	ISO 1924	≥ 33.9	≥ 25.0
Elongation in MD	%	ISO 1924	≥ 2	≥ 15
Elongation in CD	%	ISO 1924	4	5

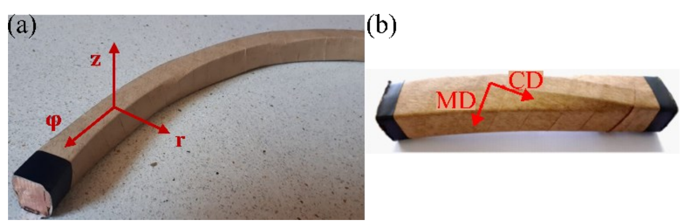

Fig. 1. (a) CTC with the axes of its cylindrical coordinate system. (b) Insulated CTC sample with the main directions of the insulation, MD and CD.

In core-type transformers the predominant component of short-circuit forces has a radial direction (see Fig. 1 (a)), so those forces were represented in the laboratory by three-point bending tests over the aged insulated CTC samples, see Fig. 2 (b), producing final deflections of 5, 10 and 20 mm in the middle of the sample. The bending tests produced fractures of different sizes in the aged paper insulation, see Fig. 2 (c). Those cracks were classified according to their size, after being studied macroscopically and microscopically, through Scanning Electron Microscopy. More details about the ageing process, the bending tests and their results can be found in [4].

B. *Thermal ageing and mechanical characterisation of the paper insulation*

Paper samples of the two types of paper insulation used in the CTC (see TABLE I) were subjected to the mentioned ageing process, see 2.1 (A). Both materials were then mechanically characterised.

- *Tensile mechanical properties:* These properties were measured according to [5], see Fig. 3 (a). The tensile strain ε_t (%) and stress σ_t (MPa) were obtained as in (1) and (2), where L_0 and L_f (mm) are, respectively, the initial distance between jawns and recorded elongation; F (N) is the recorded force; A (mm^2) is the cross-sectional area of the paper strip (product of the width, w, by the thickness, t). The detailed results of tensile tests in MD and CD can be found in [4].

$$\varepsilon_t\ (\%) = \frac{L_f - L_0}{L_0} \cdot 100 \tag{1}$$

$$\sigma_t\ (MPa) = \frac{F}{A} = \frac{F}{w \cdot t} \tag{2}$$

- *Edgewise compressive mechanical properties:* The need for obtaining these properties of the insulation arose from the observation that, after the bending of the aged CTC samples, the larger cracks appeared in areas subjected to compression, see Fig. 2 (c). However, there are no standard procedures to determine the edgewise compressive properties of thin paper. The method proposed by [6] was adapted, and cylinders made of two concentric layers of paper insulation were compressed, see Fig. 3 (b). The compressive strain ε_c (%) and stress σ_c (MPa) were obtained as in (3) and (4), where H_0 and H_f (mm) are, respectively, the initial height of the cylindrical sample (20 mm) and the recorded elongation; F (N) is the recorded force; A (mm^2) is the cross-sectional area of the cylinder (with radius R = 10 mm). The detailed results of compressive tests can be found in [7].

$$\varepsilon_c\ (\%) = \frac{H_0 - H_f}{H_0} \cdot 100 \tag{3}$$

$$\sigma_c\ (MPa) = \frac{F}{A} = \frac{F}{4\pi \cdot 10 \cdot t} \tag{4}$$

- *In-plane shear mechanical properties:* Although it is generally acknowledged that the mechanical failure of sheet materials depends on their shear properties, it is almost impossible to experimentally generate a pure shear stress condition on thin paper. Thus, most studies propose the use of approximations for the estimation of shear properties. In [8]–[11], it was considered that in-plane uniaxial tests at 35^o to the MD pronounced the shear stress while reducing the effect of normal stress components for paper materials with similar thickness and grammage to those analysed here. Therefore, the in-plane shear strength and strain of the insulation in a particular ageing state were estimated here from tensile tests over paper samples oriented at 35^o to the MD, see Fig. 3 (c). The detailed results of the estimation of in-plane shear properties can be found in [7].

- *Results of the mechanical characterisation of the paper insulation*

The results of the experiments described in section 2.1 (B) are summarised in TABLE II.

TABLE II
MAXIMUM STRAINS ± STANDARD DEVIATIONS FOR THE PLAIN KRAFT AND CREPE PAPERS, FOR THE DIFFERENT MECHANICAL SOLICITATIONS

		Tension		Compression	Shear
		$\varepsilon_{t,MD}^{max}$	$\varepsilon_{t,CD}^{max}$	ε_{c}^{max}	γ_{MD-CD}^{max}
State 0	Kraft	3.42 ± 0.25	8.22 ± 0.81	4.08 ± 0.71	5.60 ± 0.58
	Crepe	23.09 ± 1.46	11.82 ± 0.82	5.21 ± 1.45	28.76 ± 1.92
State I	Kraft	2.54 ± 0.22	7.39 ± 0.67	3.96 ± 1.68	2.94 ± 0.52
	Crepe	22.11 ± 1.02	10.37 ± 0.36	5.06 ± 1.43	11.98 ± 2.18
State II	Kraft	2.03 ± 0.16	6.09 ± 1.09	3.58± 0.92	2.60 ± 0.30
	Crepe	20.43 ± 0.72	7.79 ± 0.24	4.56 ± 1.10	10.20 ± 1.46
State III	Kraft	1.19 ± 0.05	5.50 ± 0.88	2.99 ± 0.95	1.68 ± 0.40
	Crepe	17.68 ± 1.29	3.46 ± 0.34	3.80 ± 0.92	3.23 ± 0.16

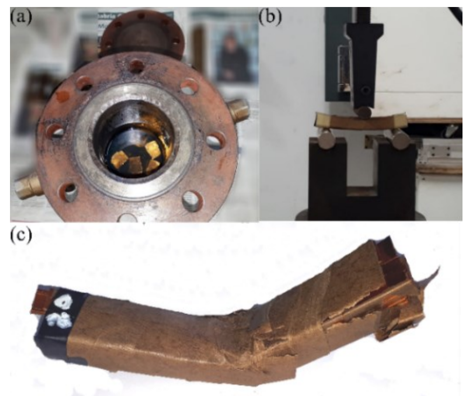

Fig. 2. Insulated CTC test pieces (a) in the vessel filled with dielectric oil, (b) ongoing a three-point bending test, (c) after a bending test with d = 20 mm.

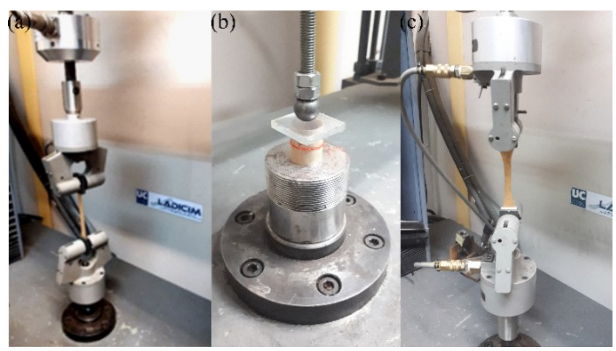

Fig. 3. (a) Tensile test over a paper sample oriented in MD. (b) Compressive test over a cylindrical paper sample. (c) Tensile test over a paper sample oriented at 35^o to MD to estimate shear properties.

2.2 *Modelling methods*

The bending tests described in section 2.1 (A) were modelled by means of a Finite Element (FE) software, see Fig. 4, to obtain the strain field over the CTC sample. Due to the adherence between the insulation paper and the copper, the strain field on both can be assimilated. The main characteristics of the FE model (geometry, supports and material properties, connections and mesh definitions) and how the results were obtained, are discussed in detail in [4]. The obtained strains were used as input in the mechanical failure model described in 2.3 (B).

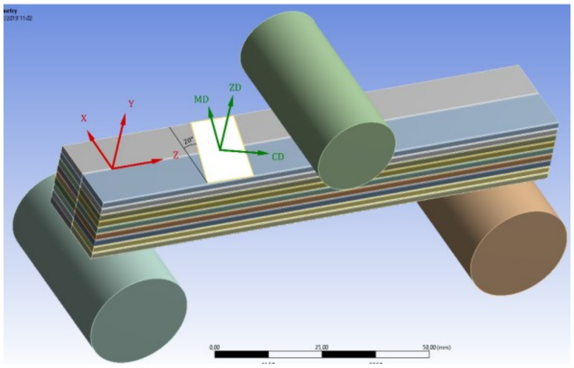

Fig. 4. Coordinate systems of the model (X, Y, Z) and of the paper material (MD, CD, ZD).

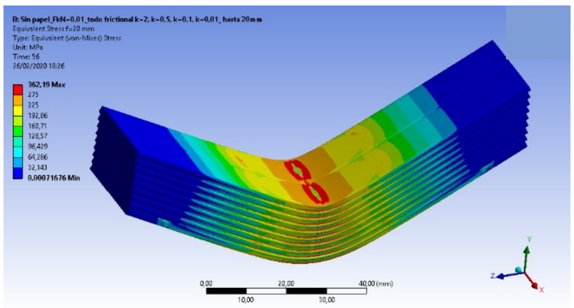

Fig. 5. Equivalent (von-Mises) stress for the simulated bending test with final deflection of 20 mm.

The numerical results showed that, for the insulation of the studied CTC subjected to bending, both the in-plane strains (tensile and compressive) in the CD and the shear strains were notably higher than the tensile strains in MD. Moreover, in line with the experiments from 2.1 (A), the compressive strains seem to be more critical for the occurrence of mechanical failure than the tensile strains.

2.3 Mechanical failure criteria for the thin paper insulation

A. Theoretical background

Electromagnetic forces over the windings of power transformers subject the paper insulation to a complex stress-strain state. An interactive mechanical failure criterion for paper materials considers a polynomial equation involving all two-dimensional stress-strain states. The criterion most commonly applied to an orthotropic lamina (such as is the case for the paper insulation) is the Tsai-Hill failure criterion [12]. The Norris criterion [13], see (5), is a particularisation of the Tsai-Hill criterion. This criterion does not intrinsically consider the differences between tensile and compressive strengths, [14], which makes it necessary to differentiate among the four stress quadrants (1st quadrant: tension MD, tension CD; 2nd quadrant: compression MD, tension CD; 3rd quadrant: compression MD, compression CD; 4th quadrant: tension MD, compression CD), see Fig. 6.

$$\left(\frac{\sigma_{MD}}{\sigma_{MD}^{max}}\right)^2+\left(\frac{\sigma_{CD}}{\sigma_{CD}^{max}}\right)^2-\frac{\sigma_{MD}\cdot\sigma_{CD}}{\sigma_{MD}^{max}\cdot\sigma_{CD}^{max}}+\left(\frac{\tau_{MD-CD}}{\tau_{MD-CD}^{max}}\right)^2\geq 1 \quad (5)$$

In the present analysis, it was more convenient to propose a mechanical failure model based on strains instead of stresses, for several reasons. First, the experiments in 2.1 (B) showed that the relative reduction in mechanical properties due to ageing was more severe for the strains than for the strengths of the paper. That supports the hypothesis that the mechanical failure of the insulation is controlled by the deformation level instead of by the stress level. Second, it is possible to assimilate the strains over the CTC and its insulation calculated through the FE model, but that would not have been possible with the stresses, as the properties of both materials totally differ. That would have required a different simulation for each insulation paper in the different ageing states, which would have been extremely unpractical and time-consuming.

Thus, a modification of the Norris Criterion is proposed here, see (6), based on the strains in the principal directions of the paper material, instead of stresses. The experiments in 2.1 (B) provided the maximum strains at failure ($\varepsilon_{MD}^{max},\varepsilon_{CD}^{max},\gamma_{MD-CD}^{max}$), while the simulation in 2.2 gave the strains ($\varepsilon_{MD},\varepsilon_{CD},\gamma_{MD-CD}$) at each node of the CTC geometry.

$$\left(\frac{\varepsilon_{MD}}{\varepsilon_{MD}^{max}}\right)^2+\left(\frac{\varepsilon_{CD}}{\varepsilon_{CD}^{max}}\right)^2-\frac{\varepsilon_{MD}\cdot\varepsilon_{CD}}{\varepsilon_{MD}^{max}\cdot\varepsilon_{CD}^{max}}+\left(\frac{\gamma_{MD-CD}}{\gamma_{MD-CD}^{max}}\right)^2\geq 1 \quad (6)$$

B. Calibration of the Norris failure criterion for the thin paper insulation

Equation (6) needs to be translated into four equations, in the four quadrants of the strain plane, for the Kraft and crepe paper in the different ageing states. The FE model allowed to determine in which quadrant of the strain plane each node of the simulated CTC is. The mechanical properties of the insulation materials detailed in TABLE II were introduced.

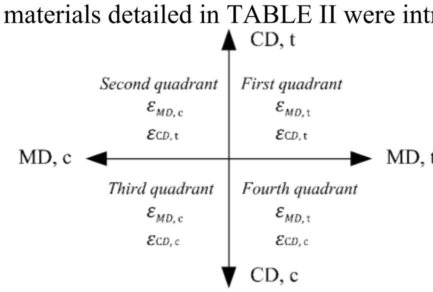

Fig. 6. Four quadrants of the strain plane.

For instance, **Errore. L'origine riferimento non è stata trovata.-Errore. L'origine riferimento non è stata trovata.** are the expressions for failure initiation of the Kraft paper, in Ageing State III, respectively, in the first, second, third and fourth quadrants of the strain plane.

$$\left(\frac{\varepsilon_{MD}}{1.19}\right)^2+\left(\frac{\varepsilon_{CD}}{5.50}\right)^2-\frac{\varepsilon_{MD}\cdot\varepsilon_{CD}}{1.19\cdot 5.50}+\left(\frac{\gamma_{MD-CD}}{1.68}\right)^2\geq 1 \quad (7)$$

$$\left(\frac{\varepsilon_{MD}}{2.99}\right)^2+\left(\frac{\varepsilon_{CD}}{5.50}\right)^2-\frac{\varepsilon_{MD}\cdot\varepsilon_{CD}}{2.99\cdot 5.50}+\left(\frac{\gamma_{MD-CD}}{1.68}\right)^2\geq 1 \quad (8)$$

$$\left(\frac{\varepsilon_{MD}}{2.99}\right)^2+\left(\frac{\varepsilon_{CD}}{2.99}\right)^2-\frac{\varepsilon_{MD}\cdot\varepsilon_{CD}}{2.99\cdot 2.99}+\left(\frac{\gamma_{MD-CD}}{1.68}\right)^2\geq 1 \quad (9)$$

$$\left(\frac{\varepsilon_{MD}}{1.19}\right)^2+\left(\frac{\varepsilon_{CD}}{2.99}\right)^2-\frac{\varepsilon_{MD}\cdot\varepsilon_{CD}}{1.19\cdot 2.99}+\left(\frac{\gamma_{MD-CD}}{1.68}\right)^2\geq 1 \quad (10)$$

Equations (11)-(14) are to be used for the crepe paper in Ageing State III, in the different strain quadrants.

$$\left(\frac{\varepsilon_{MD}}{17.68}\right)^2+\left(\frac{\varepsilon_{CD}}{3.46}\right)^2-\frac{\varepsilon_{MD}\cdot\varepsilon_{CD}}{17.68\cdot 3.46}+\left(\frac{\gamma_{MD-CD}}{1.15}\right)^2\geq 1 \quad (11)$$

$$\left(\frac{\varepsilon_{MD}}{1.67}\right)^2+\left(\frac{\varepsilon_{CD}}{3.46}\right)^2-\frac{\varepsilon_{MD}\cdot\varepsilon_{CD}}{1.67\cdot 3.46}+\left(\frac{\gamma_{MD-CD}}{1.15}\right)^2\geq 1 \quad (12)$$

$$\left(\frac{\varepsilon_{MD}}{1.67}\right)^2+\left(\frac{\varepsilon_{CD}}{1.67}\right)^2-\frac{\varepsilon_{MD}\cdot\varepsilon_{CD}}{1.67\cdot 1.67}+\left(\frac{\gamma_{MD-CD}}{1.15}\right)^2\geq 1 \quad (13)$$

$$\left(\frac{\varepsilon_{MD}}{17.68}\right)^2 + \left(\frac{\varepsilon_{CD}}{1.67}\right)^2 - \frac{\varepsilon_{MD} \cdot \varepsilon_{CD}}{17.68 \cdot 1.67} + \left(\frac{\gamma_{MD-CD}}{1.15}\right)^2 \geq 1 \quad (14)$$

III. Results and Discussion

The modification of the Norris criterion was implemented in each node of the geometry in the FE model, for each ageing state and deflection of the bending test. The predictions of the modified Norris criterion for the mechanical failure of the insulation coincide with the experimental observations in most of the cases and are conservative in all cases (for a bending deflection of 20 mm, the model predicts slightly larger cracks than those observed experimentally). The purple area in Fig. 7 shows the areas of the CTC in which mechanical failure is expected for the Kraft paper in Ageing State III and with a deformation of 10 mm. Fig. 8 shows the expected mechanical failure of the crepe insulation for the same conditions.

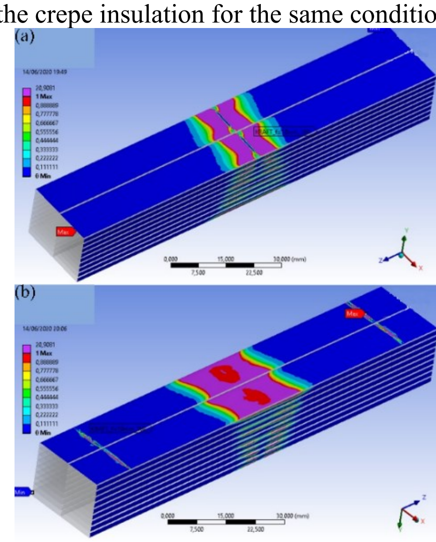

Fig. 7. Prediction of mechanical failure for the Kraft paper (a) on the upper faces and (b) lower faces of the CTC sample for Ageing State III and a final deflection of 10 mm.

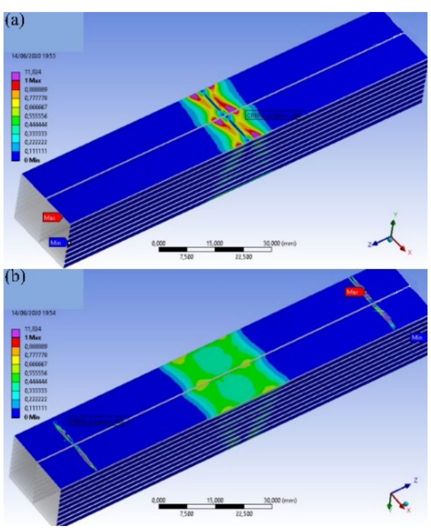

Fig. 8. Prediction of mechanical failure for the crepe paper (a) on the upper faces and (b) lower faces of the CTC sample for Ageing State III and a final deflection of 10 mm.

IV. Conclusions

The results emphasise that compression and shear mechanical properties play an essential role in the mechanical failure of paper insulation. Tensile strains are almost never the main cause for that failure, which is caused by the interaction of tensile, compressive and shear strains. However, most classic references only consider the tensile strength and the maximum strain at failure of the paper insulation. More precise experimental methods are needed for the estimation of compression and shear properties, due to their relevance.

A mechanical failure model for the thin paper insulation is a valuable predictive tool for the evaluation of the lifespan of power transformers, which can be used by paper and transformer manufacturers together with other available methods to optimise constructive characteristics in the conductors used in the windings of power transformers.

The described FE model studies a particular CTC, but can be applied to other boundary conditions, geometries, magnitudes and kinds of loads acting over the conductor. The analytical failure criterion can also be calibrated with the properties of other kinds of paper insulation in different ageing states.

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