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Cracking in paintings due to relative humidity cycles

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Abstract

A numerical study is performed using the finite element method to consider the effects of low-cycle fatigue, specifically induced through relative humidity cycles on paintings. It has been identified that there are two major crack types in paintings, these being (i) an interfacial crack (delamination) between paint and support and (ii) a through-thickness (channel) crack in the paint layer itself, arresting on the interface. Therefore a 2D plane strain model for each type of crack has been created, which both consist of an alkyd paint modelled using a visco-hyperelastic material model and a primed canvas which is assumed to behave in a linear elastic manner. To account for fatigue damage in both models, cohesive elements located along the interface or through the film thickness respectively, are used and the traction-separation law has been modified to incorporate a fatigue damage parameter. It is possible to expose the models to the same relative humidity cycles, which would typically be seen in museums, enabling the prediction of time to first crack and which crack type is more readily grown in the painting.

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Keywords: finite element; interface fracture; irreversible cohesive zones; low-cycle fatigue; thin films; through-thickness crack; viscoelastic.

1. Introduction

Easel paintings are complex composite materials that are usually constructed from a multitude of hygroscopic heterogeneous layers which show a differing dimensional response to changes in the surrounding environment (temperature and relative humidity). Two common supports/substrates used for easel paintings are canvas and wood.

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Despite the differing nature of these supports, the layers used to compose the painting are similar. Usually an animal glue is initially applied, in a process known as sizing. A ground layer is then applied, usually this is white (calcium carbonate or calcium sulphate and/or lead carbonate). Finally pigmented layers are applied on top as the design/image layers, often followed by a layer of varnish. The binding media of the ground and upper layers can include animal glue, egg, drying oils, acrylics or alkyd- depending on the date of the work, tradition and intent of the artist.

The effects of temperature and changes in relative humidity (RH) on the mechanical properties of the individual layers in a painting have been investigated (Mecklenburg (2007); Mickalski (1991)). It was shown that the constituents display different dimensional and stress-strain responses depending on the environmental conditions. A simple classification of cracks in easel paintings was first systematically applied by Keck (1969). More recently, the type of crack e.g. interfacial and channeling crack, has been identified by Jaskierny and Young (2018) where a qualitative analysis was performed on a collection of forty-three seventeenth century panel paintings displayed in the Brown Gallery located in Knole House, Kent. Channeling and interfacial cracks have also been identified, and poor adhesion qualities highlighted, when mixed-media paints are used on canvas i.e. in a combination of acrylic and alkyd paint layers (Young (2007)). Delamination between an alkyd design layer and acrylic primed canvas as a result of cyclic changes in RH has previously been investigated (Tantideeravit et al. (2013)). The work implements the irreversible cohesive zone model (Roe and Siegmund (2003)) in a finite element analysis to model the interface between an alkyd paint and primed canvas, which results in a modification to the traction-separation law to account for fatigue damage. The work only considered interfacial cracking and did not consider through-thickness cracks; an in depth understanding of crack initiation and propagation in easel paintings requires the development of such models.

There appears to be a gap in literature when considering through-thickness cracks caused by fatigue loading, with the monotonic case being more widely investigated. Most work on the subject uses the steady state energy release rate (Beuth (1992); Hutchinson and Suo (1992); Nakamura and Kamath (1992); Ho and Suo (1993); Beuth and Klingbeil (1996); Ambrico and Begley (2002); Vlassak (2003); Chai (2011)), which is said to be achieved when the crack is of a certain length, meaning the crack front remains a constant shape and the energy release rate is constant. It has been identified through a 3D finite element analysis (Nakamura and Kamath (1992)), that for a compliant film on a rigid substrate with perfect adhesion, the steady state condition is achieved when the channel crack length is approximately double the film thickness. A semi-analytical method (Beuth (1992)) has been developed based on linear elastic fracture mechanics which avoids the use of complex 3D finite element models by considering two plane strain conditions (far ahead and far behind the crack) and then stating the steady state energy release rate is the difference in the elastic strain energy of the two models. The work has been extended to consider plasticity in the substrate (Beuth and Klingbeil (1996)), caused by the stress field around the crack tip located on the film-substrate interface. Finally, the effects of plastic deformation in both film and substrate on steady state channel cracks have been considered using plane strain finite element simulations under either thermal or mechanical loading (Chai (2011)). It was shown that the inclusion of plastic deformation increases the energy release rate when compared to linear elastic materials.

In the present work, finite element simulations are used to compare the effects of daily RH cycles on the formation and propagation of crack damage in paintings. Using cohesive elements along a pre-defined crack path in the finite element model, low-cycle fatigue can be accounted for in the traction-separation law by introducing a fatigue damage parameter. Finally by exposing models for an interfacial crack and channeling crack to the same RH cycles, it is possible to determine the time to first crack and identify which crack is more readily grown in the painting.

2. Material constitutive behavior

The constitutive response of a viscoelastic material can be separated into a strain- ($\sigma_0(\varepsilon)$) and time-dependent ($g(t)$) function (Goh, Charalambides and Williams, 2004). Furthermore, a Prony series of the form

$$g(t) = g_\infty + \sum_{i=1}^{N} g_i e^{-t/\tau_i} \tag{1}$$

can be used to represent the time dependent function, where g_∞ and g_i are dimensionless constants with $g_\infty + \sum_{i=1}^{N} g_i = 1$ and τ_i the relaxation times. Finally expressing the stress response for an arbitrary strain history using a convolution integral gives

$$\sigma(t) = g_\infty \sigma_0(t) + \sum_{i=1}^{N} \int_0^t g_i e^{\left(-(t-s)/\tau_i\right)} \frac{d\sigma_0(s)}{ds} ds \tag{2}$$

which is in the form of a long-term elastic and a viscoelastic contribution. The function σ_0 can be obtained from the van der Waals hyperelastic potential W as follows

$$\sigma_0 = \lambda \frac{dW}{d\lambda} = \psi\lambda(\lambda - \lambda^{-2}) \left[\frac{\sqrt{\lambda_m^2 - 3}}{\sqrt{\lambda_m^2 - 3} - \sqrt{\lambda^2 + 2\lambda^{-1} - 3}} - \alpha \sqrt{\frac{\lambda^2 + 2\lambda^{-1} - 3}{2}} \right] \tag{3}$$

where ψ is the instantaneous shear modulus, λ_m is the locking stretch, α is the global interaction parameter and λ is the stretch ratio. The following visco-hyperelastic material parameters have been determined for an alkyd paint (Tantideeravit et al. (2013)) and are shown in Table 1.

Table 1. Van der Waals hyperelastic and Prony series material parameters.

Hyperelastic material parameters		$\psi = 75$ (MPa)	$\lambda_m = 8$	$\alpha = 0.5$		
Prony series	1	2	3	4	5	6
τ_i (s)	1.00E–01	1.00E+00	1.00E+01	1.00E+02	1.00E+03	1.00E+04
g_i	0.730	0.145	0.050	0.032	0.020	0.013

The canvas primed with gesso is assumed to be linear elastic with Young's modulus $E = 3.6$GPa and Poisson's ratio $\nu = 0.3$. An effective hygroscopic expansion coefficient β has also been determined for the alkyd paint layer $\beta = 3.05 \times 10^{-4}\%\text{RH}^{-1}$ and the canvas shows negligible dimensional with changes in RH (Tantideeravit et al. (2013)).

3. Numerical modelling

3.1. The irreversible cohesive zone model (ICZM)

The ICZM (Roe and Siegmund (2003)) accounts for fatigue damage in the finite element simulation by modifying the cohesive zone parameters through the implementation of a fatigue damage parameter. This allows the modelling of fatigue when the cohesive zone would predict an infinite fatigue life if the loading is cycled below the cohesive element failure displacement. A bi-linear traction-separation law, as seen in Figure 1, has previously been developed (Tantideeravit et al. (2013)) to model the interfacial properties between an alkyd layer on a primed canvas substrate through the use of a peel test and the parameters are shown in Table 2. As the through-thickness fracture toughness has not been obtained for the alkyd, this work uses the same traction-separation law for both interfacial delamination and through-thickness cracking.

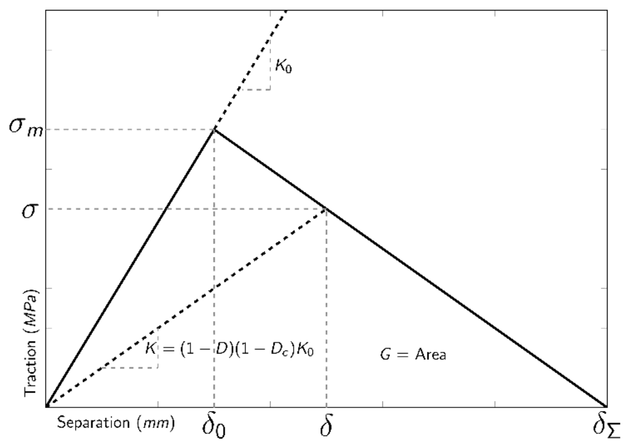

Figure 1. A bi-linear irreversible traction-separation law.

Table 2. Bi-linear traction-separation law parameters.

Traction-separation law parameters	
$G_{IC} = G_{IIC} = 0.25$ (N/mm)	$\delta_0 = 0.125$ (mm)
$K_0 = 8$ (MPa/mm)	$\delta_\Sigma = 0.5$ (mm)
$\sigma_m = 1$ (MPa)	

The stress σ in the traction-separation law is therefore calculated using

$$\sigma = (1 - D)(1 - D_c)K_0\delta \quad (4)$$

where D is the damage due to monotonic loading, D_c is the damage due to cyclic loading, K_0 is the initial stiffness and δ is the separation.

3.2. Interfacial crack model

A model to measure the crack initiation time for an interfacial fracture between an alkyd layer and canvas substrate has previously been developed (Tantideeravit et al. (2013)). The two-dimensional finite element model utilizes plane strain elements for the paint and canvas with cohesive elements along the interface, as shown by the dashed line between alkyd and canvas in Figure 2a. The alkyd and canvas were modelled using the material properties given in Section 2 and the cohesive zone from Section 3.1.

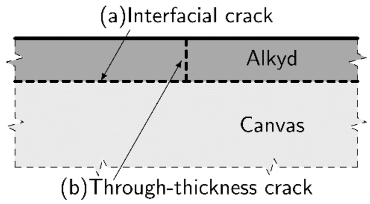

Figure 2. Painting cross-section with cohesive element location. (a) Interfacial crack. (b) Through-thickness crack.

3.3. Through-thickness (channeling) crack model

A model to measure the crack initiation time for a through-thickness crack in the paint layer has been created. It is assumed that the crack will grow at the center of the film, perpendicular to the interface, meaning a layer of cohesive elements have been placed through the film thickness (as seen in Figure 2b) and perfect adhesion is modelled between the film and substrate. Again plane strain elements have been used for the paint and canvas with the material properties in Section 2 and the cohesive traction-separation law from Section 3.1.

3.4. Relative humidity cycles

Once the RH cycles have been determined for the paintings, it is possible to implement them as boundary conditions for the two crack models in the finite element software Abaqus. It has been identified (Moran and Morgan (1990)) that on a calm day the RH cycle is approximately sinusoidal and has a maximum RH of 95%RH at 06:00 in the morning (min temp) and a the minimum of 35%RH at 15:00 in the afternoon (max temp). Therefore, this sinusoidal cycle will be implemented with different min and max values in order to determine the effect on crack initiation time. To select other min and max RH values it is possible to review museum environmental policies and assume that the min and max allowable RH's occur once a day and follow the previously mentioned sinusoidal cycle. The museum environmental policies selected are: (1) V&A Museum (Blades (2010)), min = 40%RH and max = 65%RH and (2) a strictly controlled museum (Atkinson (2014)), min = 45%RH and max= 55%RH. Table 3 shows the time (in years) that it has taken for the crack to initiate in the interfacial and through-thickness crack models.

Table 3. Time to crack initiation.

Min and max RH in daily cycle		Interfacial crack	Channeling crack
Min RH (%RH)	Max RH (%RH)	(years)	(years)
35	90	2.8	2.9
40	65	14.5	13.9
45	55	90	86

Crack initiation time was calculated as the time when the first cohesive element had lost stiffness and could no longer support a load. Except for the first case (min = 35%RH; max = 90%RH), it is shown that the channeling crack initiates slightly before the interfacial crack. This can be justified by considering the maximum stress range in the cohesive elements. For the first case (min = 35%RH; max = 90%RH) the maximum stress range is 0.05MPa for the interfacial crack compared to 0.04MPa for the channeling crack, meaning the fatigue damage accumulates at a greater rate in the case of an interfacial fracture, decreasing the time to crack initiation. For the second and third case this is reversed for example the second case (min RH = 40%RH; max RH = 65%RH) the maximum stress range is 0.018MPa for the interfacial crack compared to 0.02MPa for the channeling crack. Furthermore, as the difference between minimum and maximum RH in a cycle decreases, the percentage difference between the times for each crack to initiate increases (3.5%, 4.2% and 4.5% respectively). Nevertheless, the initiation times for both cases seem very close; highlighting the need for the through-thickness fracture properties of the paint in order to calibrate the through-thickness traction-separation law. These points will be further investigated in the future by plotting the element stress envelope and performing a parametric study on the through-thickness traction-separation law parameters.

4. Conclusion

The finite element method has been used to compare the effects of low-cycle environmental fatigue due to changes in RH on a painting which consists of an alkyd paint layer on an acrylic primed canvas. The alkyd layer has been modelled using the van der Waals hyperelastic material model in combination with a Prony series to account for time-dependency in the material and the canvas is assumed to behave in a linear elastic manner. Two models were considered: (1) a crack along the interface between the paint and canvas and (2) a through-thickness crack in the paint layer. To model crack initiation, cohesive elements were used with an irreversible cohesive zone model which incorporates fatigue damage through the use of a fatigue damage parameter.

Considering three different RH cycles it has been possible to compare the crack initiation time for both models and has been identified that there is only a small difference in the crack initiation time for a given RH cycle. For the greatest RH range considered, the interfacial crack will initiate first by a small amount, however as the RH range is reduced the process is reversed. More work is required on the subject in order to obtain a clear conclusion

Future work includes a parametric study on the through-thickness cohesive zone parameters. Furthermore, the model should be modified to account for a more complex substrate, such as wood or consideration of stress relaxation in a tensioned canvas and the effect this has on the paint layer.

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