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INFLUENCE OF BI-MATERIAL INTERFACE AND PLASTICITY INDUCED CRACK CLOSURE ON THRESHOLD VALUES

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Summary: *The paper is devoted to fatigue crack propagation in layered materials. The influence of plasticity induced crack closure on threshold values for fatigue crack propagation through interfaces between different materials layers is studied. The main aim was to estimate the influence of the loading ratio R on threshold values for crack propagation through a bi-material interface as a function of the elastic mismatch of both materials. The finite element method (FEM) is used for numerical calculations. Results obtained for different loading ratios, materials, boundary conditions and magnitude of applied loading can be generalized and used for the design of composite bodies with different material layers.*

1. Introduction and description of the problem

The proximity of a region with a different elastic modulus in combination with the presence of an interface has a pronounced influence on the fracture of composite bodies. An important problem is the influence of the interface on the fatigue crack penetrating that interface. The aim of the contribution is to estimate the influence of loading ratio R on threshold values for crack propagation through the interface.

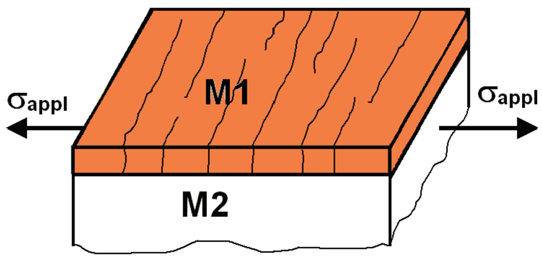

Figure1 Cracks in bi-material body touching the interface

The stress distribution around the crack tip (in the case of a crack perpendicular to the interface) can be expressed (for mode I of loading) in its general form as follows (e.g. Lin & Mar, 1976):

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$$\sigma_{ij} = \frac{H_I}{\sqrt{2\pi} \quad r^p} \quad f_{ij}(p,\alpha,\beta) \ , \tag{1}$$

where $f_{ij}(p,\alpha,\beta)$ is a known function of bi-material parameters α and β as defined in Lin & Mar (1976) and $0 < p = p(\alpha,\beta) < 1$ is the stress singularity exponent. For given materials and loading conditions, the stress distribution around the crack tip is determined by the value of the generalised stress intensity factor H_I. The value of H_I is proportional to the applied load and has to be estimated numerically. For homogeneous materials, $H_I = K_I$ is the stress intensity factor, and $p = ½$.

The criterion for estimation of threshold values for a crack touching the interface was published in Knésl et al. (2003) and Náhlík et al. (2006). In the following text only the main relationships are briefly introduced.

In a homogeneous body under conditions corresponding to high cycle fatigue, the fatigue threshold condition has the form (where $\sigma_{th}^{\hom}$ is the corresponding threshold stress):

$$K_I\left(\sigma_{th}^{\hom}\right) = K_{th} \ . \tag{2}$$

Fatigue crack will not propagate if $K_I < K_{th}$. Similarly, for a crack with the tip at the interface:

$$H_I\left(\sigma_{th}\right) = H_{th}\left(K_{th}\right) \ , \tag{3}$$

where H_{th} is the threshold value of the generalised stress intensity factor and can be determined (Knésl et al., 2003) as:

$$H_{th}\left(K_{th}\right) = K_{th}^{2p}\sigma_0^{(1-2p)}\left[\frac{f_{\hom}(\nu)}{f(\alpha,\beta,\nu)}\right]^{\frac{p}{2}} \ . \tag{4}$$

The generalised threshold value H_{th} is a function of the fatigue threshold value K_{th} of the material M2 and depends on the elastic mismatch of the materials M1 and M2: $H_{th} = H_{th}(K_{th},\alpha,\beta)$. σ_o is yield stress of M2. Instead of values K_{th} and H_{th} the fatigue threshold stress can be used as the quantity describing the behaviour of the crack. The threshold stress σ_{th} is the value of the external applied tensile stress σ_{appl} and the crack will start to grow if:

$$\sigma_{appl} > \sigma_{th} \ . \tag{5}$$

The value σ_{th} determined from (4) disregards the existence of the reversed plastic zone and closure of the fatigue crack during propagation. The phenomenon of fatigue crack closure was investigated and described by Elber (1970) as the so-called "plasticity induced crack closure". Elasto-plastic FEM calculations can be used to estimate the level of applied external loading in the sense of Newman's calculations of opening stresses, e.g. (Solanki et al., 2004). The effective value of threshold stress σ_{th}^{eff} is than:

$$\sigma_{th}^{eff} = \sigma_{th} + \sigma_{op} \ , \tag{6}$$

where σ_{th} is the threshold stress and σ_{op} is the computed opening stress. The relationship (6) can take into account various loading ratio R.

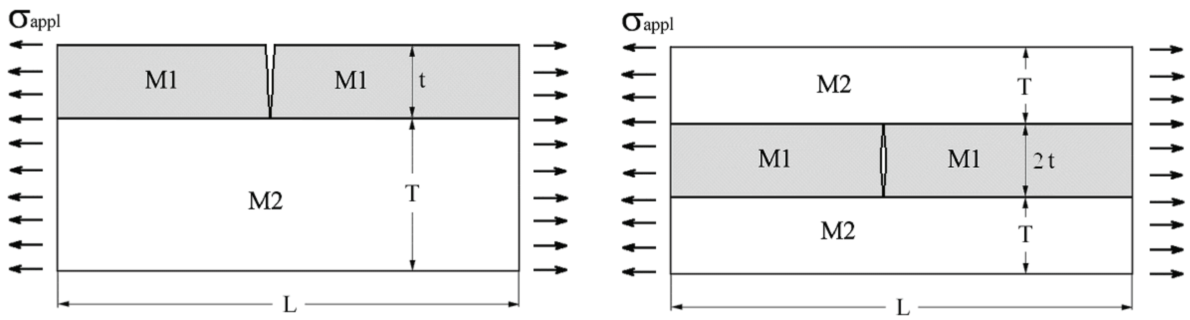
2. Numerical calculations

The procedure introduced was applied to the estimation of threshold stresses for crack propagation through a bi-material interface. Two different geometries (see Fig. 2) were considered for calculations; a bi-material body with edge crack and a bi-material body with central crack perpendicular to the interface. Cyclic loading was applied. Three different loading ratios were considered (R = 0, R = 0.5 and R = -1; were R = $\sigma_{appl,\min} / \sigma_{appl,\max}$) and three magnitudes of maximum applied stress $\sigma_{appl,\max}$ were contemplated. The level of $\sigma_{appl,\max}$ was chosen to $0.15\sigma_0$, $0.30\sigma_0$ and $0.6\sigma_0$. At the beginning of the numerical simulation the crack tip was located 0.3 mm in front of the interface. After six loading cycles with step 0.05 mm, the crack tip was situated directly at the interface. The ratio of Young's modulus (E1/E2) was varied from 0.5 to 2. The Poisson's ratio was equal to 0.3 in all cases. The opening (resp. closing) stresses σ_{op} (resp. σ_{cl}) were determined for both geometries considered, all applied loading magnitudes and loading ratios.

The procedures published in (Knésl et al., 2003 and Náhlík et al., 2006) were used for estimation of elastic threshold stresses σ_{th} . Then the numerically calculated values of closing stresses were used for estimation of the effective threshold stresses σ_{th}^{eff} (see Eq. 6), which include the plasticity induced crack closure in addition.

The calculated values of opening, resp. closing stresses are shown in Fig. 3 and 4. The resultant values of effective threshold stresses σ_{th}^{eff} for different values of E1/E2 are shown in Fig. 7 and 8.

The results correspond to plane strain approximation. As material M2 mild steel with E2 = 2.1x105 MPa, ν_2 = 0.3, σ_0 = 280 MPa, K_{th} = 5 MPa.m$^{1/2}$ (for R = 0 and R = -1) and K_{th} = 3.7 MPa.m$^{1/2}$ (for R = 0.5) was considered for calculations (Barsom & Rolfe, 1987). The material properties of M1 varied over an interval of 0.5 < E1 < 2, ν_1 = ν_2 and σ_0=280 MPa. The Chaboche material model (kinematic hardening) was used for both materials with the same hardening parameters.



(a) (b)

Figure2 The bi-material body with *edge* (a) and *central* (b) crack under (tensile) loading considered in the numerical example. T = 25 mm, t = 12.5 mm, L = 75 mm

The values σ_{th}^{eff} were normalised by the value $\sigma_{th}^{\hom}$ corresponding to fatigue threshold stress obtained from (2). σ_{th}^{eff} corresponds to the threshold stress with consideration of the plasticity-induced crack closure in terms of (6).

3. Results

A previously proposed tentative procedure (Knésl et al., 2003), modeling the propagation of a fatigue crack through the interface between two materials, is generalised in the paper. The procedure is based on an extension of the linear elastic fracture mechanics to general singular stress concentrators and can be applied to elastic bi-material bodies with interfaces (composite materials, structures with protective layers, etc.). The criterion suggested in (Knésl et al., 2003) is extended to the description of the influence of plasticity induced crack closure on fatigue threshold values. The first results from this extension were published in (Náhlík et al., 2006 and Náhlík et al., 2007).

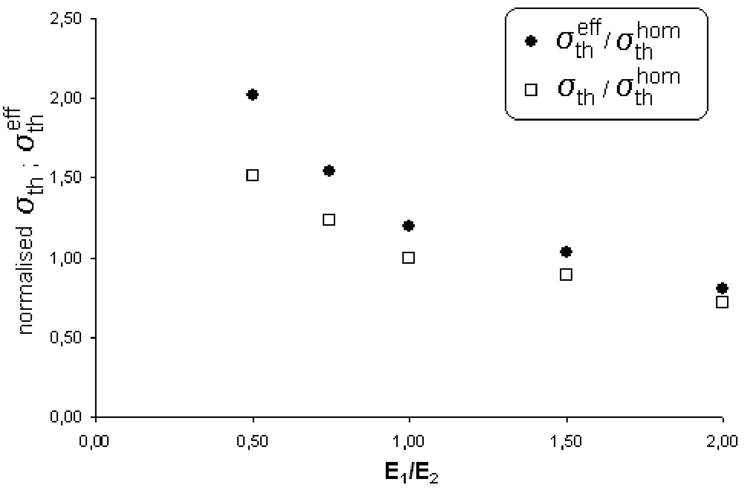


Figure 3 Dependence of the normalised effective threshold stress on Young's moduli ratio for bi-material body with *edge crack* and loading ratio R = 0

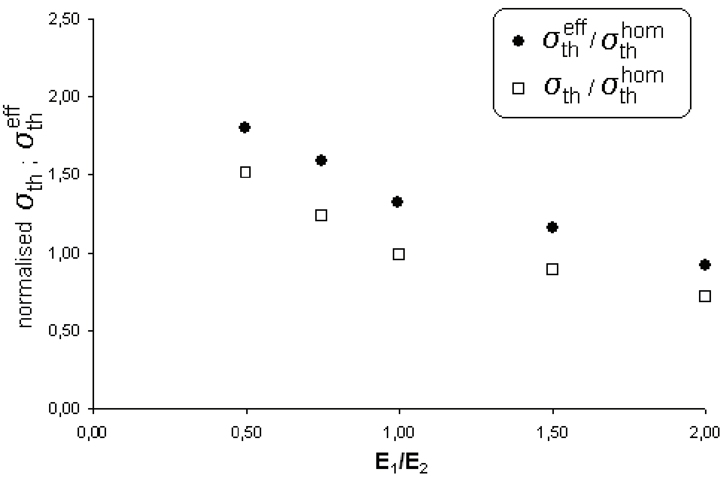


Figure 4 Dependence of the normalised effective threshold stress on Young's moduli ratio for bi-material body with *central crack* and loading ratio R = 0

The influence of a bi-material interface between two different materials on the fatigue threshold values of a crack was investigated. Numerical elasto-plastic finite element calculations were performed for a crack perpendicular to the bi-material interface and the opening (closing) stress was determined. The values of opening stresses were used for correction of elastic calculations. The effective threshold stress for a crack propagating across the interface between two materials was obtained by applying elastic threshold values and proper correction included the crack closure.

Figures 3 and 4 show increase of effective threshold stresses in comparison with calculations without consideration of plasticity induced crack closure. The increase of σ_{th}^{eff} (in average about 20 percent) is significant and is necessary to consider its magnitude for better determination of beginning of fatigue crack propagation through the bi-material interface.

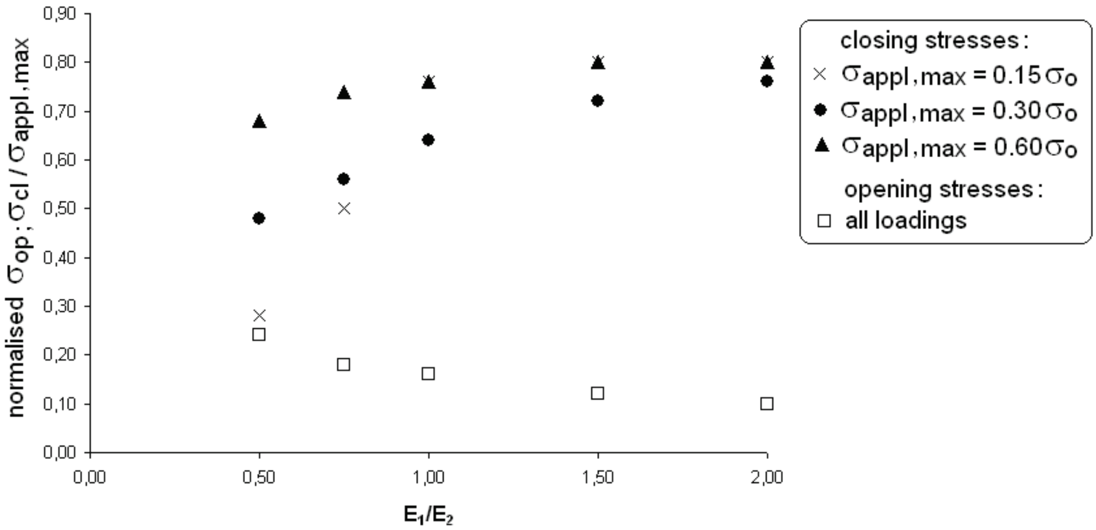


Figure5 Dependence of opening and closing stresses on Young's moduli ratio for different magnitudes of applied loading. Results correspond to the bi-material body with *edge crack* and R = 0

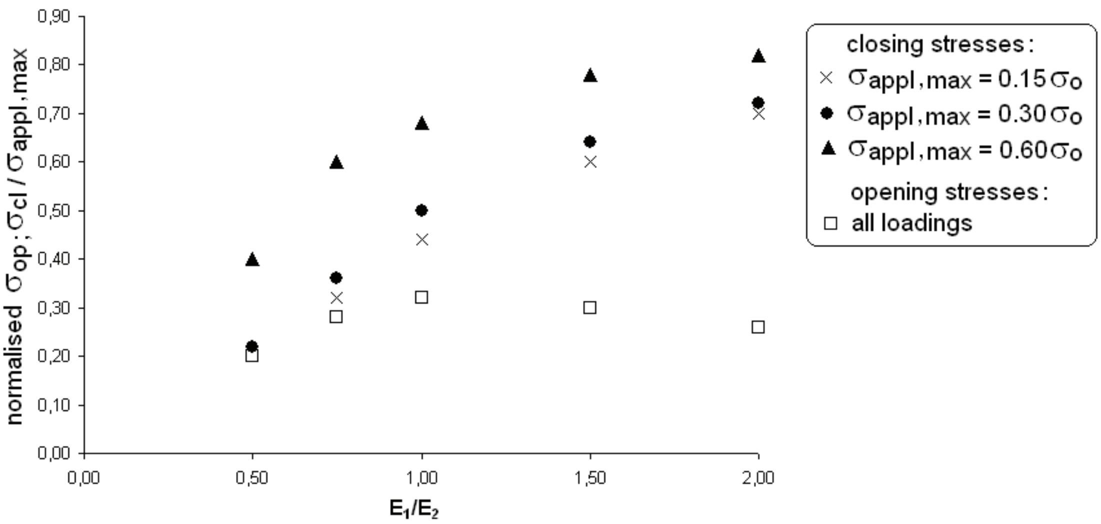


Figure6 Dependence of opening and closing stresses on Young's moduli ratio for different magnitudes of applied loading. Results correspond to the bi-material body with *central crack* and R = 0

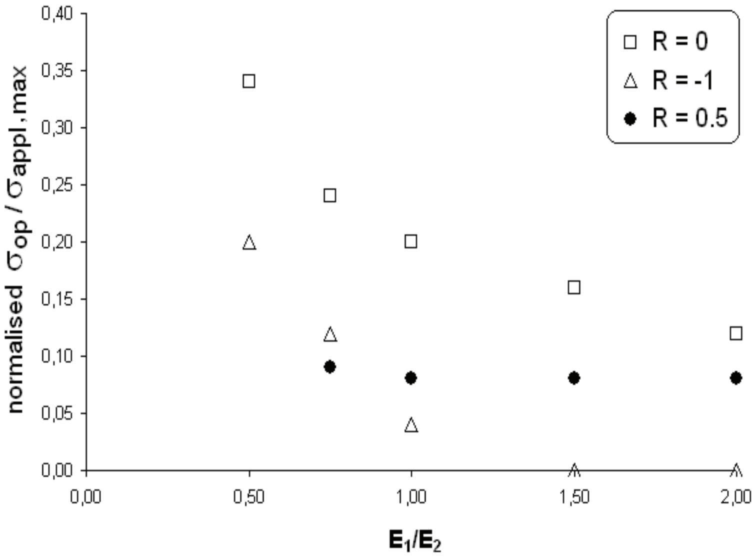


Figure7 Dependence of opening stresses on E_1/E_2 ratio for three different loading ratios. Results correspond to the bi-material body with *edge crack* and $\sigma_{appl,\max} = 0.30\sigma_o$

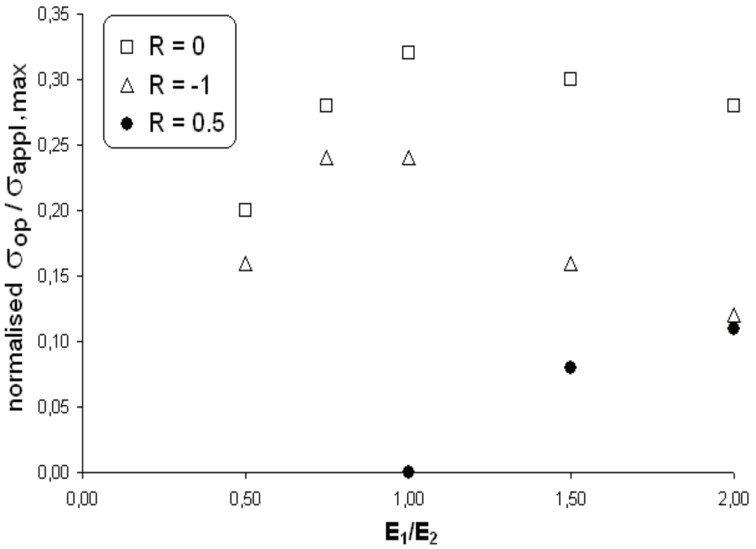


Figure8 Dependence of opening stresses on E_1/E_2 ratio for three different loading ratios. Results correspond to the bi-material body with *central crack* and $\sigma_{appl,\max} = 0.30\sigma_o$

The opening stresses increase with a decreasing ratio of Young moduli (E1/E2). The closing stresses indicate the opposite trend (see Fig. 5 and 6). The magnitude of external applied stress does not influence the ratio $\sigma_{op} / \sigma_{appl,\max}$ or the effective threshold values. The biggest opening stress and the biggest influence of plasticity induced crack closure occurring simultaneously was obtained for pulsating tensile applied stress (at R = 0). The smallest opening stress was determined at R = -1 (Fig. 7). These results are in correspondence with the behaviour of a crack in homogeneous material (Solanki et al., 2004).

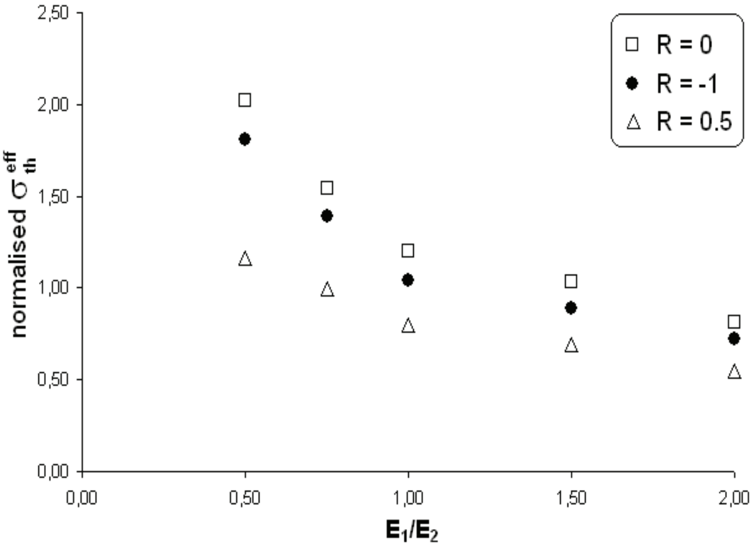


Figure9 Dependence of the normalised effective threshold stresses on Young's moduli ratio for different loading ratio: bi-material body with *edge crack*

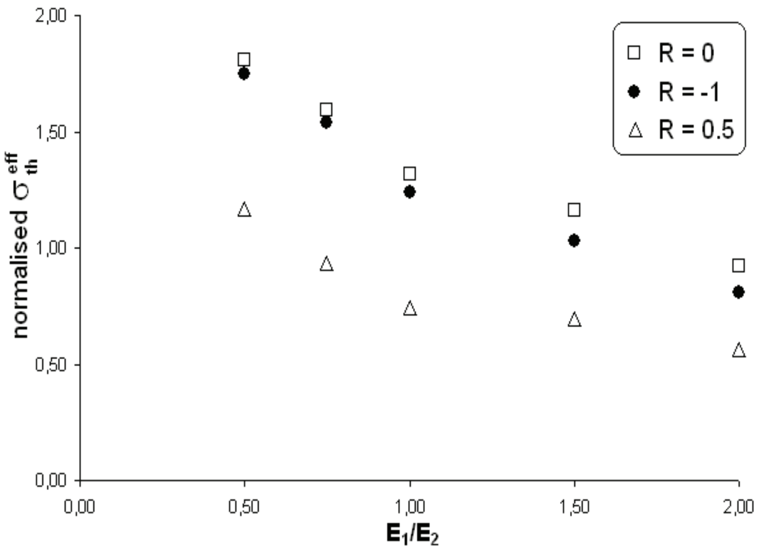


Figure10 Dependence of the normalised effective threshold stresses on Young's moduli ratio for different loading ratio: bi-material body with *central crack*

Figures 9 and 10 show the increase of effective threshold values due to plasticity induced crack closure for different Young's moduli ratio and loading ratio. It follows from the results presented that the corresponding fatigue threshold value can be strongly influenced by the presence of a material interface. The correction for the existence of a plastic wake behind the tip of a propagating fatigue crack allows for an estimation of the threshold values for crack propagation through the bi-material interface. The results obtained show (see Fig. 9 and 10) that for M1, a softer material than M2 (E1<E2) the fatigue threshold value increases. In the opposite case (E1>E2), the fatigue threshold value decreases in comparison with a crack propagation in homogeneous material M2. The results for the case of edge and central crack are similar, but it is clear that the influence of Young's modulus ratio is stronger in the case of the edge crack (see Fig. 9 and 10). Figures 9 and 10 show the effective threshold stresses for different loading ratios as well. It is evident that the strongest influence of fatigue crack closure is reached at R = 0.

4. Conclusion

The contribution presented was focused on determination of influence of bi-material interface and plasticity induced crack closure on threshold values of fatigue crack propagating through the interface. For determination of effective threshold values the approach based on generalized linear elastic fracture mechanics published by Knésl et al. (2003) and Newman's (Solanki, 2004) method of estimation of opening stresses were together used. The effective threshold stresses were calculated for different magnitude of applied stress, different loading ratio, for two different geometries and in dependence on ratio of Young moduli between individual material components of composite. For evaluation of residual stresses the finite element method was used. The results obtained show strong influence of material interface on threshold values for crack propagation through interface. The strongest influence of fatigue crack closure was reached at loading ratio R = 0. The magnitude of fatigue crack closure in individual cases is not significantly influenced by Young moduli ratio of materials components of the composite.

The results obtained could be used for the design of new materials with interfaces (composite materials, etc.) and for safer service life of structures made from the materials to which we have referred.

5. Acknowledgements

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6. References

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