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Modelling of nonlinear behaviour of structural elements at high temperatures

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Introduction

During extreme events, such as a fire, structural elements exhibit significant nonlinear response, generally in the form of material nonlinearity and geometric nonlinearity. This study considers the influence of various nonlinear parameters on the mechanical response of structural elements subjected to high temperatures. Thermal loading is applied in simple forms - constant temperature increase and/or constant thermal gradient.

The Problem

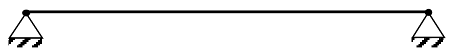

Figure 1: A simply supported beam with restrained translations

Elastic Analysis

Constant temperature increase

The elastic beam of Fig. 1 subjected to constant temperature increase will expand linearly with temperature. If possibility of buckling is ignored (the beam is assumed to be stocky) the horizontal reaction will increase linearly with temperature and inclusion of geometric nonlinearity will have no influence.

Constant thermal gradient

Exclusion of nonlinear geometry makes the central deflection increase linearly with increasing thermal gradient (Fig. 2a). However, this thermal bowing does not cause reactions at the supports (Fig. 2b). The inclusion of nonlinear geometry causes axial forces which limit the central deflection as seen in Fig. 2a. Clearly these cause reactions which are shown in Fig. 2b. The temperature in all figures refers to the temperature at the bottom face of the beam.

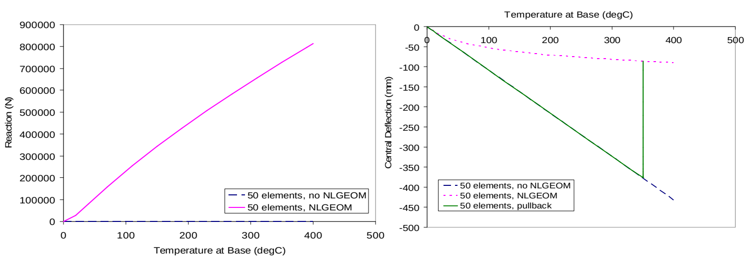

Figure 2: (a) Deflection and (b) reaction in an elastic beam with and without nonlinear geometry when a constant thermal gradient is applied

Constant temperature increase and constant thermal gradient

The exclusion of nonlinear geometry causes central deflection to increase linearly due to thermal gradient only. As before, the inclusion of nonlinear geometry limits central deflection. Initially deflection is larger when nonlinear geometry is present due to thermal expansion of the beam dominating its behaviour, however as the thermal gradient applied increases thermal bowing is induced and the overall deflections are limited by the restraint at the supports. This is shown in Fig. 3.

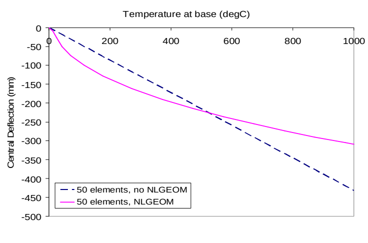

Figure 3: Deflection in an elastic beam with and without nonlinear geometry when a constant temperature increase and a constant thermal gradient is applied

Plastic Analysis

This study next applies strain softening plastic material properties to the beam, as recommended by Eurocode 2 (1996), Design of Concrete Structures – Part 1.2 General Rules – Structural Fire Design, *European Committee for Standardisation (CEN)*, and considers the issue of mesh sensitivity for structural components subjected to high temperature loading.

Constant temperature increase

Figure 4 shows the support reactions for the materially nonlinear beam discretised using different numbers of finite elements. The response is different if strain softening slope is taken as a material property, with mesh insensitivity being restored once the softening slope is treated as a structural property dependant on element size. The presence of nonlinear geometry has no effect on the behaviour of the beam in this case.

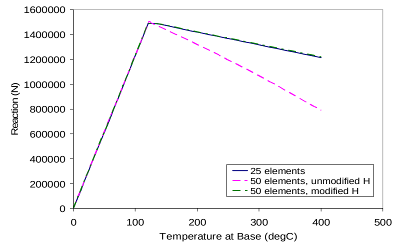

Figure 4: Reaction due to uniform temperature increase in a materially nonlinear beam with different mesh discretisations and softening moduli

Constant thermal gradient

In Fig. 5, when nonlinear geometry is present, mesh insensitive behaviour is seen due to the absence of strain localisation - the thermal gradient causes uniform thermal bowing and hence uniform plastic strain along the beam's length. When nonlinear geometry is absent no plastic yield occurs as no stresses are induced (see Fig. 2).

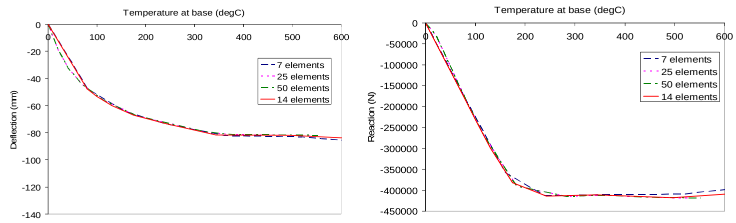

Figure 5: (a) Deflection and (b) reaction in a materially nonlinear beam when a constant thermal gradient is applied with different mesh discretisations

Constant temperature increase and constant thermal gradient

When nonlinear geometry is absent thermal gradient does not cause plastic yield in a pinned beam, and hence causes no reaction forces. The horizontal reaction comes entirely from thermal expansion and is identical to that seen in Fig. 4. This causes the reaction force to be mesh sensitive, something not seen when nonlinear geometry is included (Fig. 6b). As seen previously in Fig. 3, the central deflection when nonlinear geometry is present starts off larger than that when it is absent, before becoming smaller due to the effects of thermal bowing being limited by the restraints.

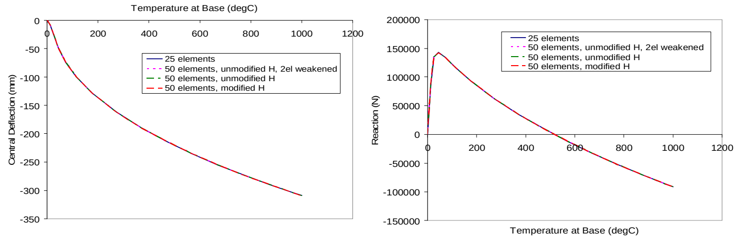

Figure 6: (a) Deflection and (b) reaction in a materially nonlinear beam when both a uniform thermal expansion and a constant temperature gradient are applied with different mesh discretisations and softening modulus.

Conclusions

This study on a simple beam element illustrates that geometrical nonlinearity plays an extremely important role in high temperature analysis. Strain softening, when treated as a material property as suggested by Eurocode 2 (1996), can lead to mesh sensitive results.