

Thermochemical assessment of the load-bearing capacity of steel-reinforced elastomeric bearings subjected to fire loading

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ABSTRACT

This paper addresses the characterization and analysis of the thermochemical behavior of steel-reinforced elastomer (polychloroprene) bearings during fire loading. Based on results obtained from thermogravimetry (TGA) and differential scanning calorimetry (DSC) experiments, a thermochemical model capturing the effective behavior of the elastomer is proposed. The obtained material model is implemented in a finite element program for evaluating the evolution of temperature and material degradation within steel-reinforced elastomeric bearings commonly employed in engineering practice. In a first step, the analysis tool is applied to the re-analysis of experiments, where sections of a steel-reinforced elastomeric bearing are subjected to a pre-specified temperature load while measuring the temperature increase within the steel and elastomer layers. Measured data and simulation results show good agreement, finally paving the way for the application of the proposed analysis tool to the analysis of the time-dependent heat penetration of steel-reinforced elastomeric bearings in the course of a fire incident. The obtained results provide useful information on the remaining load-bearing capacity of elastomeric bearings finally entering the safety analysis of buildings and bridges supported by these bearings.

1. Introduction

Steel-reinforced elastomeric bearings (see Fig. 1) are widely used as supports of buildings and bridges, providing the required flexibility by avoiding unwanted restraints and/or serving as seismic isolators. Their structure – alternating horizontal layers of steel and elastomer – leads to high stiffness in the vertical direction, with the horizontal (shear) stiffness being significantly lower. In case of a fire incident, thermal loading causes degradation of the elastomer, affecting the mechanical properties of the bearing and, consequently, the load-carrying capacity and integrity of the supported engineering structures. Hence, knowledge about the response of the bearing under thermal loading is of central importance for the assessment of the safety of structures, which is required in the design process of new structures as well as in the maintenance and enhancement of existing structures.

A characteristic mechanical property of elastomers such as polychloroprene, which is considered in this work, is its high stiffness in compression in relation to its shear stiffness (i.e., its Poisson's ratio is close to 0.5 and, hence, $E_c \approx 3G_c$ where E_c and G_c refer to Young's and shear modulus, respectively, see, e.g., van den Bogert and de Borst [6]). The high vertical stiffness of steel-reinforced elastomeric bearings is attributed to the steel plates inducing an oedometer-like stress state by hindering the lateral strain within the elastomer layers. Consequently,

in addition to the shear modulus G_c , the area of an elastomer layer A in relation to its thickness h influences the overall stiffness of the bearing [5]. In addition to the temperature dependence of the elastic properties of elastomer (even at moderate temperatures, see, e.g., [2,11]), the major reduction in load-bearing capacity arises in the course of thermal degradation at elevated temperatures – as occurring in fire incidents. Hereby, caused by chemical conversion, increasing porosity, and embrittlement, the degraded elastomer can no longer contribute to the load-carrying mechanism. As the remaining (non-degraded) part of the elastomer still contributes to the load-carrying mechanism of the elastomeric bearing, its quantification is crucial for determining the (time-dependent) remaining stiffness of the bearing in the course of a fire incident.

The characterization and modeling of the thermal degradation behavior of polychloroprene (standardly used in elastomeric bearings) using thermogravimetry experiments among other methods is reported in literature (e.g., [9,3,18,30,19]). Respective kinetic models of different levels of sophistication provided in [8,3,25] are discussed in the modeling section of this paper. As regards the situation in steel-reinforced elastomeric bearings, the low thermal conductivity of elastomer implies low rates of heat penetration, while steel exhibits significantly higher thermal conductivity enhancing the heat penetration into the bearing. The contribution of the elastomer to the heat

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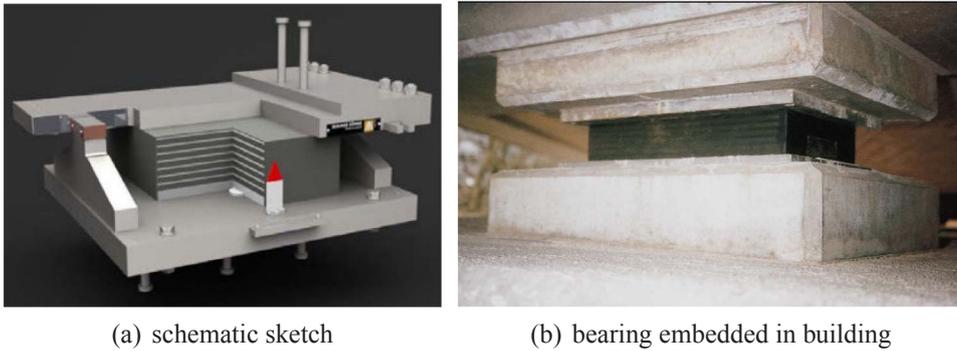


Fig. 1. Steel-reinforced elastomeric bearings [22].

penetration was even considered as neglectable in [16,17] where the heat transfer within layered bearings, serving as seismic isolators, was analyzed. Bearings subjected to more elevated temperatures originating from fire loading were treated in [24] in the framework three-dimensional finite element simulations. Based on the numerically obtained heat penetration, the residual load carrying behavior was assessed by the assumption that only those parts of the base area bounded by a certain isotherm (threshold value equal to 200 °C) were contributing to the load bearing. Thermochemical couplings associated with the degradation of the elastomer were disregarded. Experimental examinations on steel-reinforced bearings were reported in [14] where the effect of mechanical loading on the evolution of mechanical properties of lead-rubber bearings was investigated. Therein, the mechanical force applied on the bearing during thermal loading was found to have minor influence on the evolution of properties.

In consideration of the latter result, possible effects from thermochemical-mechanical coupling are disregarded in the present paper while focusing on the thermochemical aspect of the degradation process within the polymer layer. A combination of characterization and validation experiments on the one hand and finite-element simulations on the other hand is applied for obtaining new insights into the degradation mechanism and, hence, the safety assessment of steel-reinforced elastomeric bearings. For developing a material model capturing the thermochemical behavior of elastomer, respective properties are determined by means of thermogravimetry (TGA) and differential scanning calorimetry (DSC) experiments, which are reported in Section 2 of this paper. The underlying thermochemical material model based on these results and its implementation into finite element simulations is presented in Section 3. In Section 4, the simulation tool is applied for the reanalysis of a section of a steel-reinforced elastomeric bearing subjected to fire loading. Results from these experiments as well as respective simulation results are presented and discussed. In Section 5, parameter studies are performed, providing insight into the significance and influence of material, geometry and load parameters on the heat penetration rate and, accordingly, on the evolution of the residual stiffness of the bearing. The paper closes with concluding remarks in Section 6.

2. Material characterization

For characterizing the thermochemical behavior of polymer, the mass loss in the course of heating was determined in TGA experiments performed with the device Netzsch STA 449 [27]. Moreover, the respective reaction enthalpies were determined in DSC experiments using the device Netzsch DSC214 Polyma [28]. For both characterization methods (see, e.g., [10] for further details), different heating rates and different atmospheres (Nitrogen and Oxygen atmosphere) were considered.

Results from TGA experiments are shown in Fig. 2, where polychloroprene samples were heated from room temperature to 900 °C at heating rates ranging from 2 to 25 K/min. Observable basic tendencies

agree well with measurements in earlier publications such as in [9]. In the temperature range of 250–500 °C, a mass loss by $\approx 40\%$ can be observed with only little difference between the different atmospheres and heating rates. In case of nitrogen atmosphere, the mass decrease goes only slightly beyond 40% for temperatures above 500 °C, showing no influence of the heating rate. According to [19,3,18,30], the first stage of mass loss is mainly associated with dehydrochlorination and, accordingly, production of HCl. In nitrogen atmosphere, it is followed by the pyrolysis of intermediary products, finally yielding a residual mass composed of carbonaceous char. On the other hand, the presence of oxygen finally leads to complete degradation of the sample when further increasing temperatures beyond 500 °C (see Fig. 2(b)).

While also a heating rate of 2 K/min was considered in the TGA experiments for additional information, DSC experiments were focused on the most relevant heating rates related to present application case (i.e., 10 K/min and 25 K/min). According to the results shown in Fig. 3, the first stage of degradation (associated with dehydrochlorination) is accompanied by a considerable heat release indicating an exothermic reaction in both atmospheres. In agreement with TGA results, no significant heat release/consumption can be observed after this peak at pyrolytic conditions (Fig. 3(a)) in nitrogen atmosphere whereas results indicate additional exothermic processes in oxygen atmosphere (Fig. 3(b)).

Fig. 4 displays the temperature-dependent specific heat c_p at constant pressure and temperatures between 40 and 180 °C, also obtained by DSC experiments.

3. Thermochemical modeling

3.1. Field equation

In the course of thermal loading of elastomeric bearings, the following physical/chemical mechanisms have to be considered:

- (i) storage/release of heat due to the change of temperature,
- (ii) heat transfer due to thermal conduction,
- (iii) heat transfer due to mass flux of gas,
- (iv) heat consumption/release in the course of degradation of elastomer,
- (v) transition of the initially solid elastomer to gaseous constituents during degradation.

Using Fourier's law of heat conduction, the underlying field equation for the heat-transfer problem capturing the above-mentioned physical/chemical mechanism reads (cp., e.g., [26])

$$\rho c \dot{T} = \nabla \cdot (\lambda \nabla T) - \dot{m}_g \cdot (c_g \nabla T) + \dot{h}, \quad (1)$$

with the variables specified as follows:

ρ	density of solid material [kg/m ³]
c	specific heat of solid material [J/(kg K)]

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