



Effects of model configurations on the post-fire performance of lead-rubber bearings

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Abstract

The study investigates how model configuration assumptions in heat-transfer modelling affect the thermal field and the post-fire mechanical performance of lead-rubber bearings (LRBs). Because prior studies generally model only the isolator while others include connection components, the authors address this gap by comparing three FE model configurations: A) isolator only, B) isolator+upper/lower steel flange plates, and C) isolator+flange plates+connected RC column. Thermal and mechanical analyses are performed in ANSYS Workbench. Fire exposure is defined using the ISO-834 standard fire curve with 20, 30, and 40 minutes of heating, resulting in nine scenarios (3 configurations×3 durations). Temperature-dependent degradation of rubber properties is incorporated in the thermo-mechanical phase; peak nodal temperatures from the thermal analysis are transferred as the initial thermal state for the structural model. Mechanical loading includes 10 MPa vertical compressive stress and lateral displacement corresponding to 100% shear strain. Results show that post-fire horizontal stiffness and strength degradation increase with fire duration and depend strongly on the model configuration. Configurations B and C exhibit a clear reduction in horizontal stiffness after fire exposure, while the isolator-only case (A) shows the smallest deviation from the pre-fire response. The inclusion of steel flange plates (B) leads to more pronounced degradation, consistent with intensified heat transfer into the isolator; adding the RC column (C) slightly moderates thermal transfer compared with B but still produces significant post-fire softening. Overall, the study highlights that neglecting flange plates and connected structural elements can underestimate internal temperature distribution and misrepresent post-fire performance, underscoring the need to include these components in FE modelling for realistic fire assessment.

1. Introduction

The use of base isolation systems has become increasingly widespread due to their effective protection of both structural and non-structural components against earthquake effects [1,2]. In recent years, with the growing interest in these systems, their use has expanded beyond critical structures

such as hospitals and administrative buildings to include residential buildings as well. In base-isolated buildings, the isolation level is typically utilized as a parking or storage area. Moreover, this level may also contain electrical and gas installations and certain components of structural health monitoring systems. Therefore, in such buildings, the likelihood of a fire occurring in the isolation level, whether

due to seismic events or other causes, is considerably high. The elevated ambient temperatures that develop during a fire critically affect structural elements. In addition, a fire that may occur at the isolation level can lead to significant capacity losses in base isolation systems, particularly in elastomeric bearings [3,4]. This situation can jeopardize structural safety; therefore, it is necessary to assess whether the isolators can remain in service after the fire or whether they need to be replaced immediately.

In addition to comprehensive studies on the behavior of structural elements under fire and elevated temperature effects, research focusing on how the heating of the lead core during cyclic loading alters the mechanical properties of elastomeric bearings and the seismic performance of the superstructure has also gained significant prominence in the literature [5–8]. However, despite their vulnerability to elevated temperatures, the number of studies addressing the effects of elevated temperature or fire conditions on seismic isolation units and base-isolated structures remains quite limited. Existing research includes fire testing on bearings [9], investigations on the effectiveness of fire-protective coatings [10], experimental and numerical examinations of thermo-chemical behavior [11], evaluations of isolator degradation in reinforced concrete (RC) buildings using numerical fire scenarios [12], and the development of fragility curves incorporating cooling-heating processes for bearings [13]. In the majority of these studies, comprehensive heat transfer analyses were conducted to accurately capture heat propagation within the isolators. In addition, using the isotherm approach, the pre-fire conditions of the isolators and the mechanical performance losses that occur after fire exposure were evaluated in detail and in a comparative manner.

Lead-rubber bearings are not thermally isolated components. Their rubber layers and steel shims are vulcanized into an integrated assembly that is connected to the supporting structure through upper and lower steel flange plates and anchor systems. Therefore, the extent of the finite-element model may directly affect the heat-flow paths available to the bearing. Previously mentioned studies have provided valuable evidence on the fire resistance of elastomeric bearings, fire-protection strategies, thermo-mechanical degradation, and the post-fire behaviour of isolated structures. However, a specific modelling issue remains insufficiently resolved: the sensitivity of the predicted thermal field and post-fire mechanical response to the extent of the bearing-connection assembly included in the numerical model. More specifically, it remains unclear whether a model containing only the LRB can adequately represent the thermal and mechanical consequences of fire exposure, how much the upper and lower steel flange plates alter heat transfer toward the interior of the bearing, and whether the adjacent RC member moderates or amplifies this effect through its thermal mass. These questions cannot be answered through individual temperature or response

predictions alone, because the LRB geometry, exposure history, and analysis procedure must be kept identical while only the modelling configuration is changed. A controlled comparison is therefore needed to determine the potential error associated with omitting connection components and to identify the modelling level required for a realistic fire assessment of LRBs.

To address this gap in the literature, heat transfer analyses were conducted in this study for lead rubber bearings (LRBs) under three different model configurations, and the effects of these model configurations on isolator performance were evaluated in detail. The model configurations considered in this context are: (i) the case in which only the isolator is included in the model (Configuration A), (ii) the case formed by adding the upper and lower steel flange plates to the isolator (Configuration B), and (iii) the case in which the column to which the isolator system is connected is also incorporated into the model (Configuration C). Thermal and mechanical analyses were performed in ANSYS Workbench [14] for the specified model configurations. By incorporating the temperature-dependent material properties of rubber into the model, thermo-mechanical analyses were carried out, and the degradation in secondary stiffness after fire exposure was determined. Based on these analysis results, the pre-fire and post-fire force-displacement relationships of the isolators were defined. The sequential procedure adopted for evaluating the post-fire mechanical properties of lead-rubber bearings is presented in Fig. 1.

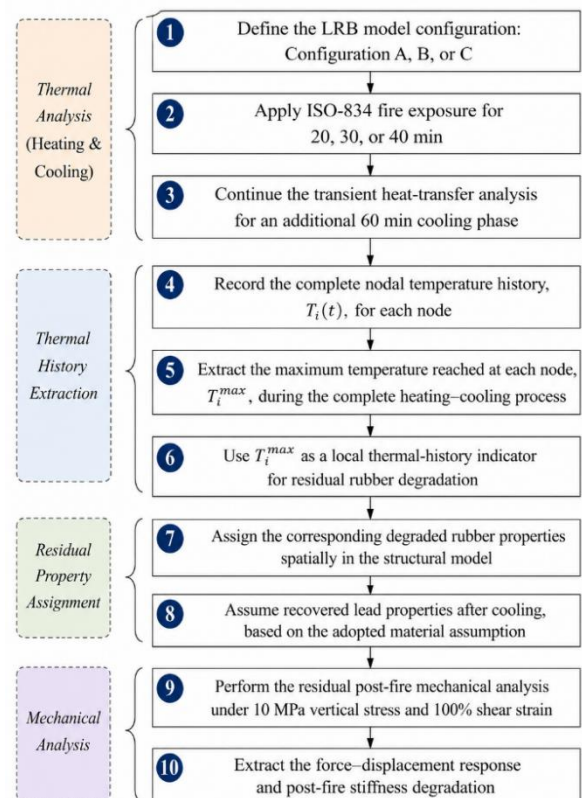


Fig. 1. Sequential procedure used for post-fire thermo-mechanical analysis of LRBs

2. Fire scenarios and geometrical configuration of the isolation models

This section presents the fire scenarios and modeling parameters adopted to evaluate the thermo-mechanical behavior of selected LRBs under varying model configurations. Three distinct model configurations (Configurations A, B, and C) were defined to examine the influence of model configurations on the thermal response of the isolators. Configuration A includes only the isolator itself. Configuration B incorporates the upper and lower steel flange

plates together with the isolator. Configuration C further extends the model by adding the RC column to which the isolation system is connected. An overview of the three configurations considered in this study is provided in Fig. 2. Fire scenarios were established using the ISO-834 [15] standard fire curve, and exposure durations of 20, 30, and 40 minutes were selected to represent short- and medium-duration fire events likely to occur in isolation levels. By combining the three model configurations with the selected fire durations, a total of nine scenarios were created. The scenarios considered in this study are summarized in Table 1.

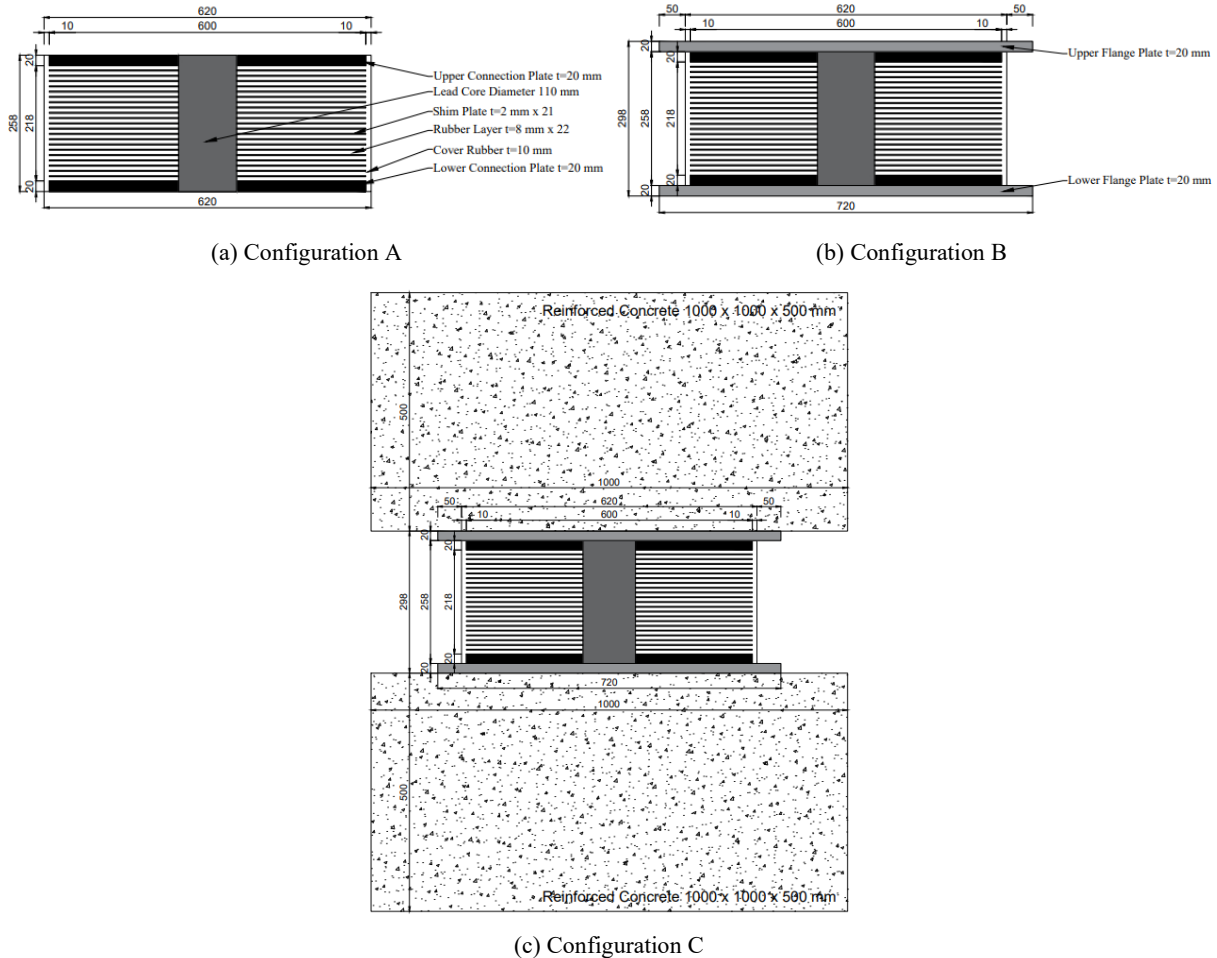


Fig. 2. Model geometries for the three model configurations used in the analysis

Table 1. Selected fire scenarios and model configurations

Scenario	Model configuration	Description	Fire Duration	Fire Curve
S1-A20	Configuration A	Only isolator modeled	20 min	ISO-834
S2-A30			30 min	
S3-A40			40 min	
S4-B20	Configuration B	Isolator + steel flange plates	20 min	ISO-834
S5-B30			30 min	
S6-B40			40 min	
S7-C20	Configuration C	Isolator + steel flange plates + RC column	20 min	ISO-834
S8-C30			30 min	
S9-C40			40 min	

3. Development of numerical model

In this study, the FE model of the bearings and their components was developed in ANSYS Workbench [14] (Fig. 3). For thermal analysis, models were generated by meshing the individual rubber layers, steel shims, lead core, and RC columns with three-dimensional solid elements (SOLID87 and SOLID90), enabling an accurate representation of heat transfer within the isolator. A fully bonded condition was assigned to the rubber–steel contact surfaces as well as to the interface between the lead core and the surrounding rubber–steel assembly [13]. The thermal simulation was performed by adopting Fourier’s law, and no interaction between the thermal and mechanical fields was considered in this phase of the analysis. The thermal properties employed in the model, including thermal conductivity (k), specific heat (c_p), and density (ρ), are listed in Table 2. These parameters were assumed to remain constant with temperature as a simplifying modelling assumption, consistent with Mazza and Alesina [13], and were adopted from the relevant literature [16–19]. A nominal mesh size of 30 mm was adopted for both the transient thermal and static structural analyses. With this mesh size, the FE models consisted of 19,170 elements for Configuration A, 23,140 elements for Configuration B, and 37,912 elements for Configuration C. Preliminary mesh-sensitivity trials indicated that this mesh size provided sufficiently stable thermal and mechanical response predictions while maintaining a reasonable computational time. For Configurations A and B, the ISO-834 [15] fire exposure was applied to all external surfaces exposed to air. For Configuration C, the same fire exposure was applied to all air-exposed surfaces except for the upper and lower faces of the RC column. These surfaces were excluded because they represent the continuity of the column beyond the finite-element domain. The fire-exposed surfaces were subjected to convection and radiation model configurations using a heat-transfer coefficient of 25 W/m²K and a surface emissivity of 0.70 [20]. The transient thermal analyses were performed using a fixed time increment of 60 s.

In the mechanical analysis, models were generated by using three-dimensional solid elements (SOLID186). The mechanical properties of lead were assumed to fully recover after cooling from fire exposure [16,17,21]. Wu et al. [9]

reported only very limited change in the yield strength, which is primarily governed by the lead core, in post-fire mechanical tests of seismic rubber bearings. These findings support the assumption that the mechanical properties of the lead core undergo only limited degradation after thermal exposure and subsequent cooling. In contrast, the reduction in rubber properties due to elevated temperatures was directly incorporated into the analysis. To document the residual material model for rubber, the temperature-dependent elastic modulus and Poisson’s ratio values reported by Kaiser et al. [22] are presented in Table 3. In the reference experimental study, rubber specimens were conditioned at ageing temperatures of 5°C, 25°C, 50°C, and 90°C. For each temperature level, the elastic modulus and Poisson’s ratio were measured, and the corresponding shear modulus was calculated. The shear modulus values were then normalized by the room-temperature value to describe the relative stiffness degradation of rubber. Based on these normalized data, a regression model was developed, as shown in Fig. 4, to relate the maximum temperature experienced by the rubber material to the corresponding degraded mechanical properties. The regression model indicated an approximately linear reduction in shear modulus with increasing temperature. Since the available experimental data were limited to 90°C, the fitted relationship was extrapolated beyond this range; this extrapolation suggested that the normalized shear modulus would approach zero at approximately 294°C. Therefore, the extrapolated part of the model was used as a simplified degradation assumption rather than as a directly validated experimental response.

Table 2. Average thermal properties of structural materials used in LRBs

Material	k (W/mK)	c_p (J/kg K)	ρ (kg/m ³)
Rubber	0.16	1700	1300
Steel	50.0	450	7800
Concrete	0.72	780	2300
Lead	35.0	130	11300

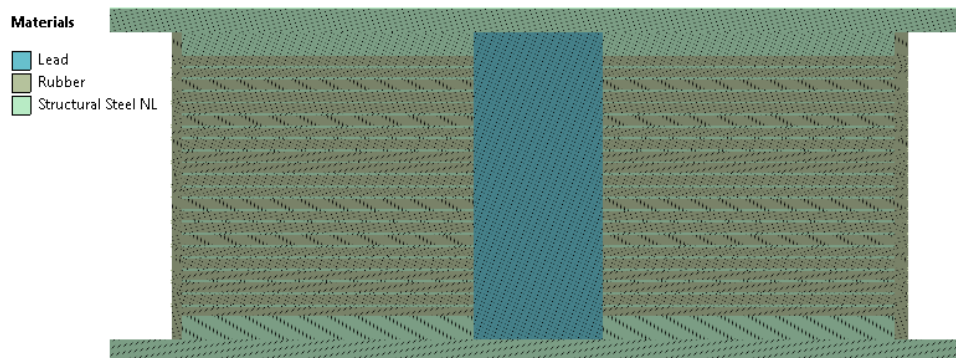


Fig. 3. The FE model of the bearings and their components

Table 3. Young's modulus and Poisson's ratio of rubber material at different ageing temperatures, based on the experimental data reported by Kaiser et al. [22]

Temperature [°C]	Young's modulus [MPa]	Poisson's ratio
5	1.92	0.420
25	1.87	0.430
50	1.61	0.445
90	1.40	0.450

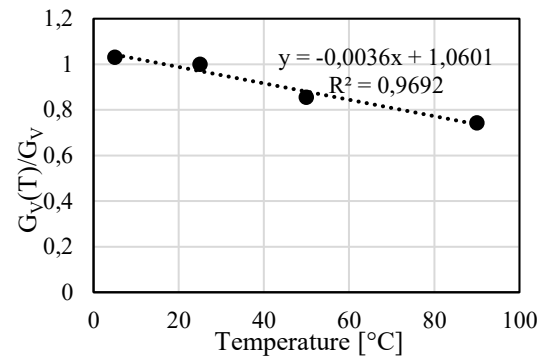


Fig. 4. Regression model describing the reduction in shear modulus of rubber material

Table 4. Adopted material properties for mechanical analysis

Material	Model	Young's modulus (MPa)	Poisson's ratio	Yield strength (MPa)	Initial shear modulus (MPa)	Incompressibility parameter (MPa ⁻¹)
Steel	Bilinear	200000	0.30	250	---	---
Lead	Bilinear	14000	0.44	12.99	---	---
Rubber	Neo-Hookean	---	---	---	0.392	0.001

Lead and steel components were idealized using bilinear force–displacement relationships, while the rubber layers were represented through a Neo-Hookean hyperelastic formulation. The parameters defining these constitutive models are provided in Table 4. In the thermo-mechanical phase of the analysis, a sequential one-way thermo-mechanical procedure was adopted to evaluate the residual post-fire response of the LRBs. For each fire scenario, the transient heat-transfer analysis was continued for an additional 60 min after the end of the ISO-834 heating period to account for the cooling phase. The node-wise peak temperatures obtained during the complete heating–cooling analysis were used to define the residual degradation state of the rubber material. These values were not interpreted as a physically simultaneous temperature field, since the maximum temperature at different nodes may occur at different times. Instead, the maximum temperature reached at each node was used as a local thermal-history indicator, because residual rubber degradation is governed by the highest temperature experienced locally during fire exposure, even if the material subsequently cools down. Therefore, using only the temperature field at the end of cooling would not adequately represent the residual damage state. The resulting spatially varying degraded rubber properties were then assigned in the mechanical analysis. A vertical compressive stress of 10 MPa was applied to the top plate of the isolator, and the bottom plate was assigned a cyclic lateral displacement history corresponding to a shear strain amplitude of 100%. The cyclic loading protocol consisted of one loading–unloading cycle between the positive and negative target displacement amplitudes, and the same displacement history was applied to all configurations and fire-duration scenarios. These loading levels were selected to represent the vertical loading and lateral deformation

demands commonly experienced by seismic isolation bearings and are consistent with the ranges considered in previous fire-performance studies of seismic rubber bearings [9]. Large-deformation effects were included in the structural analyses. Automatic time stepping was adopted with an initial time step of 0.1 s, a minimum time step of 0.001 s, and a maximum time step of 0.2 s.

4. Results and discussion

This section presented the findings obtained from the thermal and mechanical analyses conducted for the lead-rubber bearings under the selected fire scenarios and model configurations. The results were examined with emphasis on the influence of fire duration, temperature distribution within the isolator, and the role of structural configuration on both thermal response and post-fire mechanical performance. Comparative evaluations were provided to clarify the sensitivity of isolator behavior to changes in model configurations and thermal exposure levels.

4.1. Thermal response of the isolators

The time-dependent temperature profiles obtained at different locations within the lead-rubber bearings are presented in Figs. 5–7. The results showed that the temperature development was strongly affected by both the model configuration and the fire duration. In general, Configuration B produced the highest temperatures, followed by Configuration C and Configuration A. This trend was particularly evident at the upper-level monitoring points, where the influence of the steel flange plates on heat transfer became more pronounced. For example, at Point #7, the maximum temperatures after 20 min of fire exposure were approximately 53.7°C, 228.9°C, and 199.3°C for Configurations A, B, and C, respectively. The same trend

became stronger as the fire duration increased; at 30 min, the corresponding temperatures reached 70.5°C, 351.1°C, and 301.7°C, while at 40 min they increased to 86.9°C, 458.8°C, and 393.5°C. Similar differences were also observed at the other upper-level points. At Point #8, the maximum temperature under 40 min exposure increased from 69.7°C in Configuration A to 329.7°C in Configuration B and 255.8°C

in Configuration C. At Point #9, the corresponding values were 71.0°C, 249.5°C, and 188.4°C, respectively. These results indicated that the steel flange plates in Configuration B created additional heat-transfer paths toward the isolator, whereas the RC column in Configuration C partly moderated this effect.

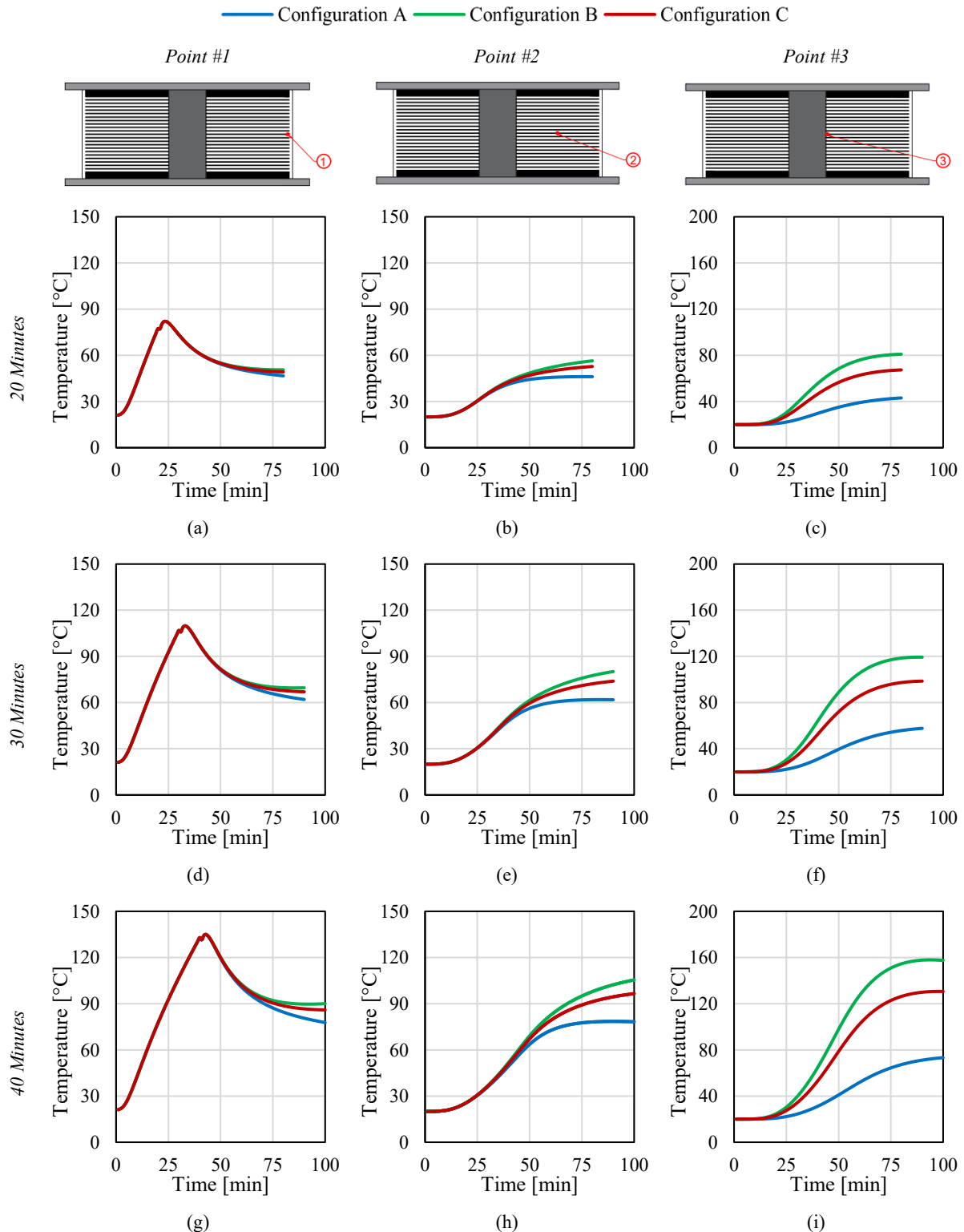


Fig. 5. Time-dependent temperature profiles at three mid-level locations within the LRBs

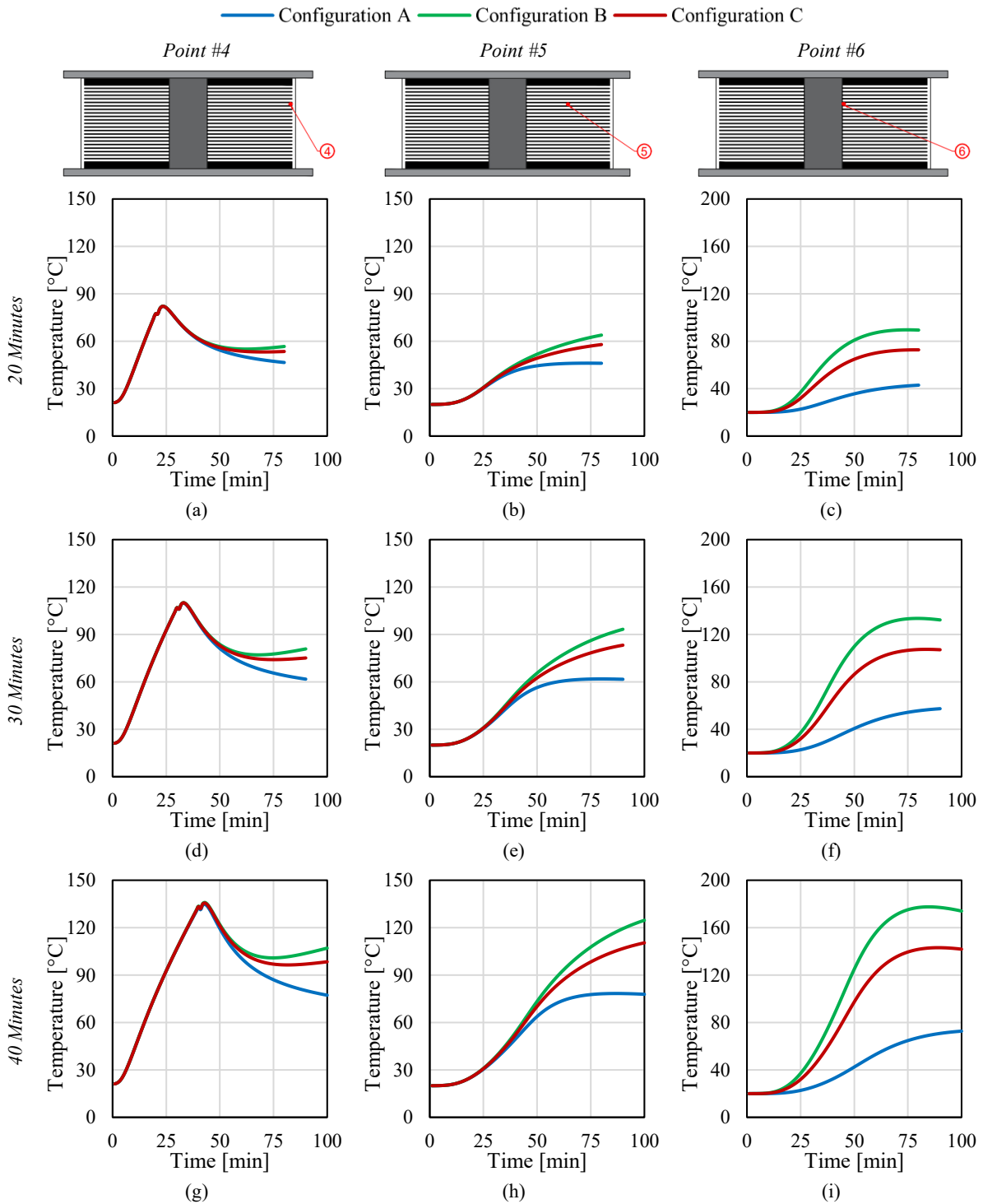


Fig. 6. Time-dependent temperature profiles at three quarter-level locations within the LRBs

The isolator-only scenarios (S1-A20, S2-A30, S3-A40) consistently exhibited the lowest temperature rise, reflecting the limited thermal pathways available for inward heat transfer. In contrast, the addition of steel flange plates in Configuration B increased vertical and radial conductivity, resulting in higher temperatures in scenarios S4-B20, S5-B30, and S6-B40. The presence of the reinforced concrete column in Configuration C relatively reduced this effect compared with Configuration B, as observed in scenarios S7-C20, S8-C30, and S9-C40. However, the temperature distribution in

Configuration C was still considerably more critical than in the isolator-only scenarios.

The distribution of maximum temperatures presented in Fig. 8 clearly demonstrates the sensitivity of the thermal response to both fire duration and model configuration. As the duration of fire exposure increased, the high-temperature zones expanded progressively throughout the isolator, particularly in the scenarios incorporating steel flange plates. Configuration B (S4-B20, S5-B30, and S6-B40) exhibited the most pronounced temperature concentrations, confirming that the upper and lower flange plates formed highly effective

thermal pathways between the fire-exposed surfaces and the internal components of the bearing. Owing to their high thermal conductivity, these plates rapidly transferred heat toward the central region and, in particular, directly to the lead core. Once heated, the lead core, which also possesses relatively high thermal conductivity, acted as an additional internal heat-transfer pathway and redistributed thermal energy toward the surrounding rubber–steel assembly. Consequently, the temperature distributions indicate a combined heat-propagation mechanism: heat advanced from the external surfaces toward the interior through the flange

plates, while the heated lead core promoted the subsequent spread of heat from the central region toward the outer portions of the isolator. This interaction resulted in a broader and more severe thermal field than that observed in Configuration A. In Configuration C (S7–S9), the presence and thermal mass of the RC column slightly moderated the temperature rise compared with Configuration B; nevertheless, the flange plate–lead core conduction mechanism remained effective, and the resulting temperature distribution was still considerably more critical than that obtained for the isolator-only configuration.

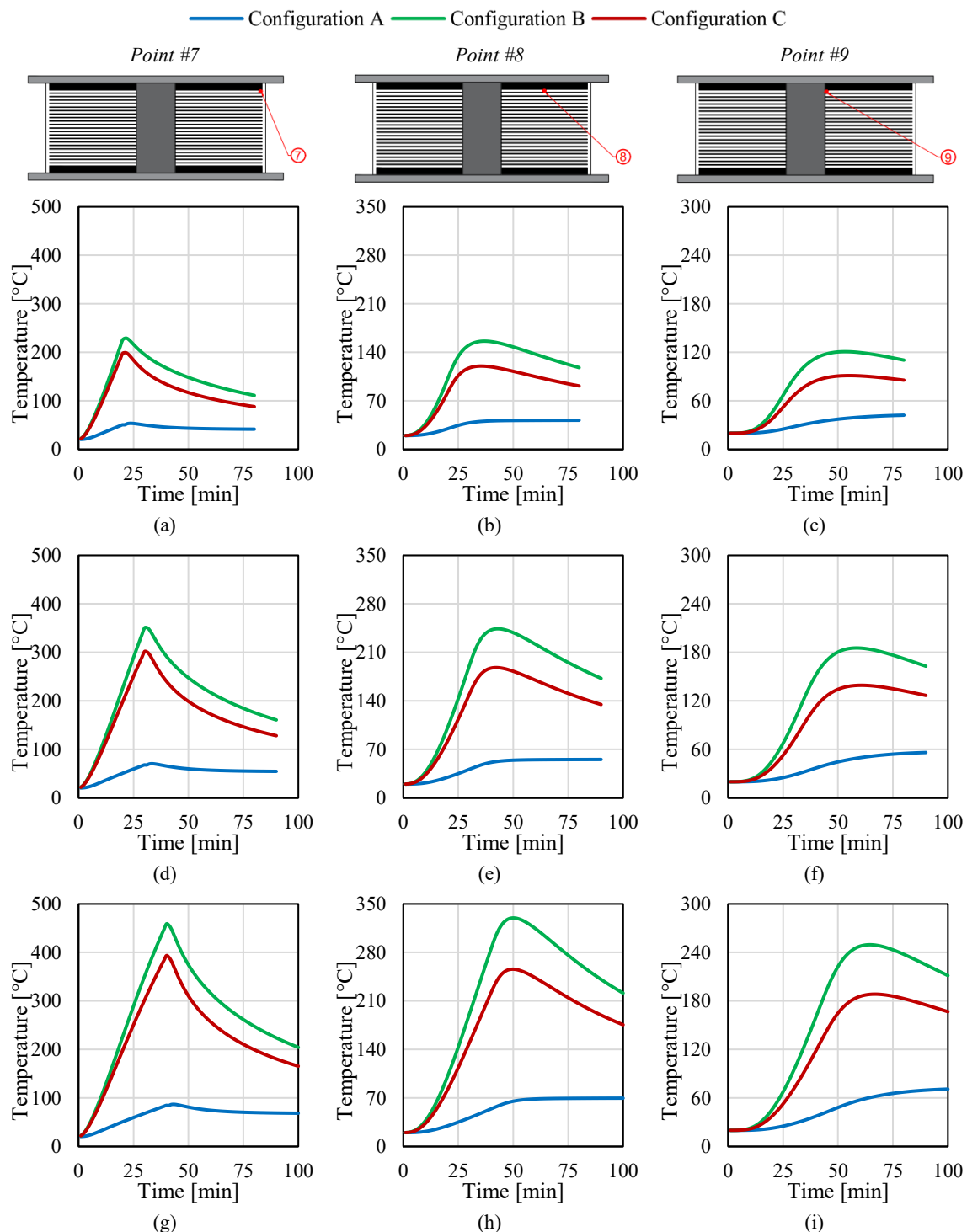


Fig. 7. Time-dependent temperature profiles at three upper-level locations within the LRBs

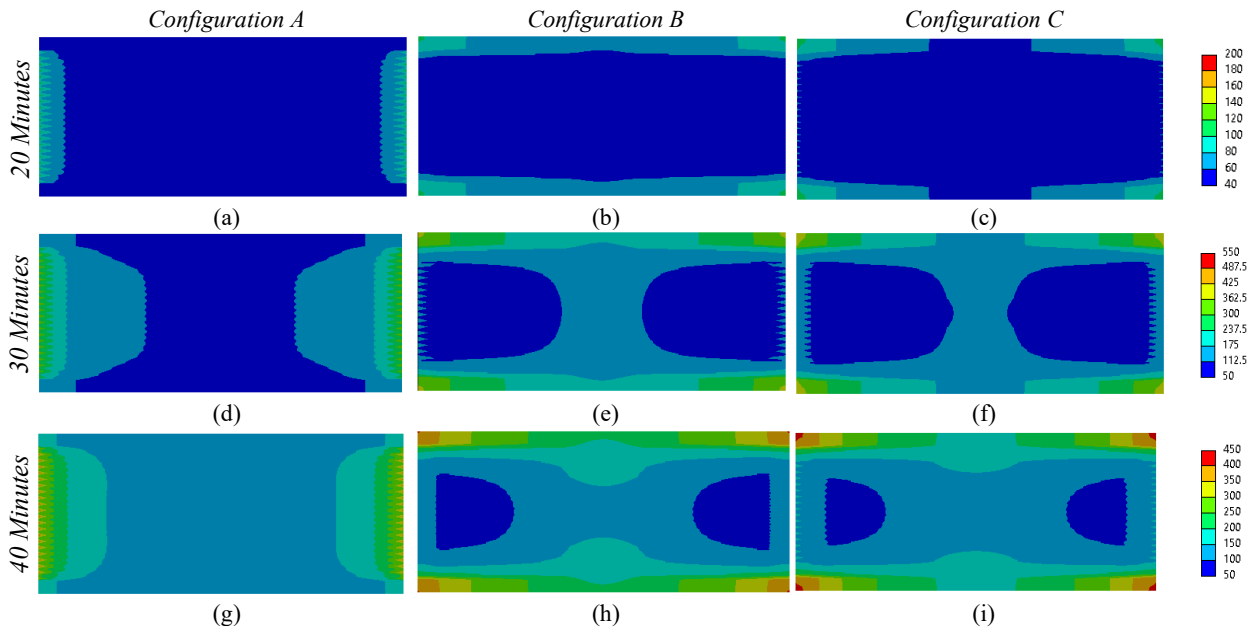


Fig. 8. Maximum temperature distributions within the LRBs for each configuration under different thermal exposure durations

4.2. Post-fire mechanical response of the LRBs

The effects of elevated temperatures on the mechanical response of the LRBs were comparatively examined through the pre- and post-fire force–displacement responses obtained for each configuration and fire duration. Figs. 9 and 10 present the lateral hysteretic behavior of the isolators after they were subjected to 20-, 30-, and 40-minute heating scenarios. In Configurations B and C, the force–displacement responses demonstrated a distinctive reduction in horizontal stiffness after fire exposure, with the degradation increasing as the heating duration increased. The isolator-only case (Configuration A) showed the least deviation from the pre-fire response, indicating a relatively limited thermal impact on its mechanical properties. In contrast, the inclusion of steel flange plates in Configuration B led to more pronounced lateral stiffness degradation, particularly under the 30- and 40-minute fire scenarios, consistent with the higher temperature concentrations previously identified in the thermal analyses. Although the RC column slightly moderated thermal transfer compared with Configuration B, its post-fire mechanical response still showed significant softening relative to the pre-fire condition.

The mechanical results presented in Figs. 9–10 confirmed that post-fire degradation in stiffness was strongly influenced by both fire duration and model configuration. The scenarios associated with higher thermal demand produced the most pronounced mechanical deterioration, particularly in cases where steel components intensified heat transfer to the isolator. These findings show that the post-fire mechanical

response is closely related to the thermal demand generated by the surrounding steel and RC components.

To quantify the post-fire mechanical degradation, the secondary stiffness was used as the main response parameter. In this study, the secondary stiffness was calculated from the slope of the post-yield force–displacement relationship. The reduction ratio was then determined by comparing the post-fire secondary stiffness with the corresponding pre-fire value for each configuration and fire duration. As summarized in Table 5, Configuration A exhibited the lowest stiffness reduction, ranging from 13.04% to 26.01% as the fire duration increased from 20 to 40 min. Configuration B showed the most severe degradation, with reductions of 22.72%, 42.28%, and 79.80% after 20, 30, and 40 min, respectively. Configuration C exhibited an intermediate response, with corresponding reductions of 19.27%, 32.51%, and 51.18%. These results quantitatively confirm that the steel flange plates intensify the thermal demand on the LRB, whereas the connected RC column partly moderates this effect but does not eliminate the post-fire stiffness loss.

No significant change was observed in the characteristic or yield strength values in the present analyses. This result is consistent with the adopted material assumption that the mechanical properties of the lead core recover after cooling. Since the characteristic strength of LRBs is primarily governed by the lead core, the strength-related parameters remained essentially unchanged, and the quantitative degradation assessment was therefore focused on the secondary stiffness affected by the temperature-induced degradation of rubber.

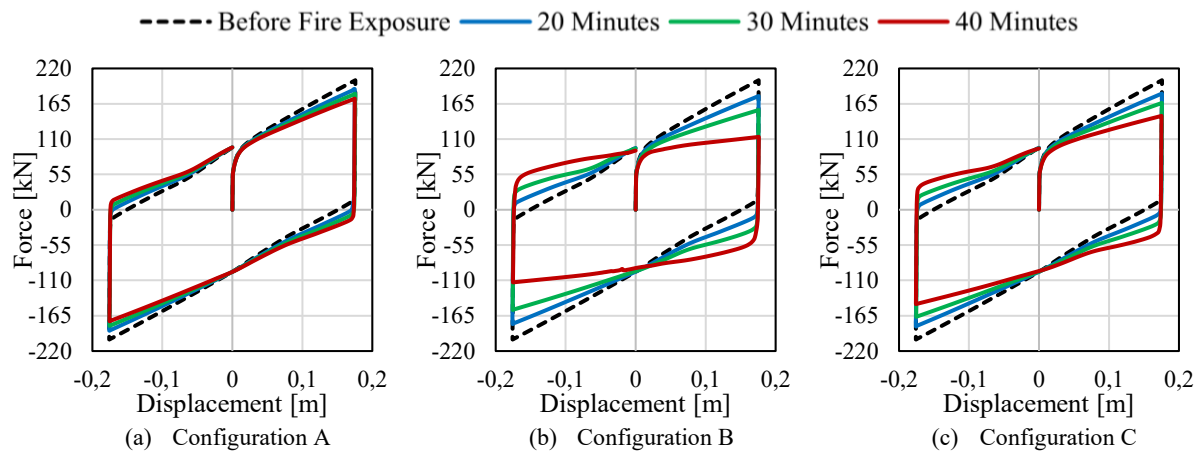


Fig. 9. Post-fire force–displacement response of the LRBs under different thermal exposure durations for each configuration

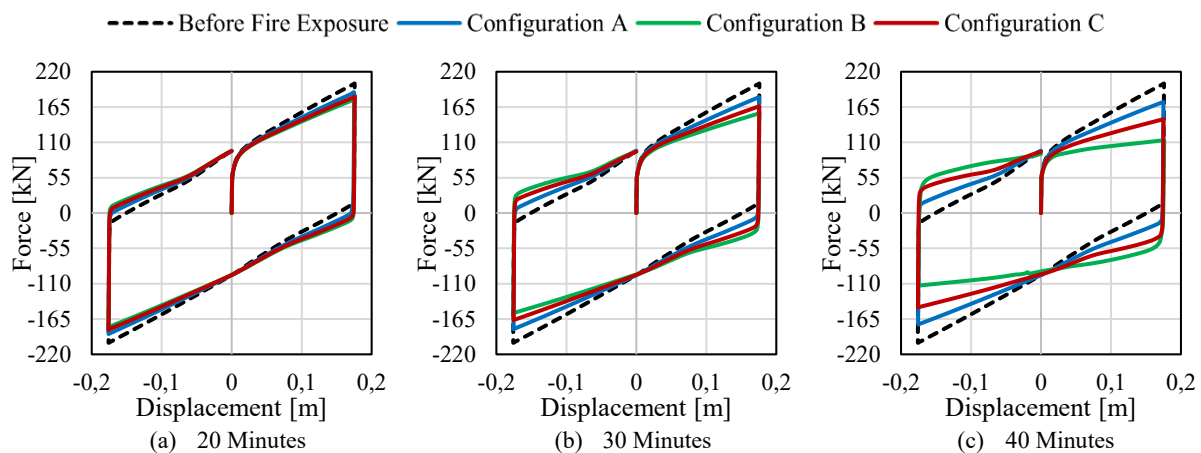


Fig. 10. Post-fire force–displacement response of the LRBs under each configuration for different thermal exposure durations

Table 5. Reduction in post-fire secondary stiffness relative to the pre-fire condition

Model Configuration	Fire Duration	Pre-fire Secondary Stiffness (kN/m)	Post-fire Secondary Stiffness (kN/m)	Reduction in Secondary Stiffness (%)
Configuration A	20 min	614.86	534.67	13.04
	30 min		496.08	19.32
	40 min		454.93	26.01
Configuration B	20 min	614.86	475.17	22.72
	30 min		354.87	42.28
	40 min		124.19	79.80
Configuration C	20 min	614.86	496.35	19.27
	30 min		414.98	32.51
	40 min		300.16	51.18

5. Conclusion

The primary aim of this study was to evaluate the thermal and post-fire mechanical behavior of lead-rubber bearings under three fire scenarios and three model configurations, thereby assessing the extent to which model assumptions and fire severity influenced isolator performance. Thermal and mechanical analyses were performed in ANSYS Workbench [14] for the specified model configurations. By incorporating the temperature-dependent material properties of rubber into

the model, thermo-mechanical analyses were carried out, and the degradation in isolator response after fire exposure was determined. Based on these analysis results, the pre-fire and post-fire force–displacement relationships of the isolators were defined.

The thermal analyses showed that fire duration and structural configuration had a decisive influence on the temperature distribution within the isolators. Scenarios incorporating steel flange plates (Configuration B) produced

the highest temperature concentrations, while the RC column in Configuration C moderated heat transfer slightly yet still resulted in significantly elevated temperatures compared with the isolator-only case. These findings demonstrated that the surrounding structural components of bearings played a critical role in defining thermal demand. The post-fire mechanical analyses revealed a clear degradation in lateral stiffness that increased with longer heating durations. The most severe mechanical deterioration occurred in scenarios where steel components intensified heat transfer toward the isolator. The isolator-only configuration exhibited the smallest deviation from the pre-fire response, while Configurations B and C experienced substantial softening consistent with the thermal exposure patterns. Overall, these findings highlighted the necessity of incorporating the isolators as well as the steel flange plates and connected structural elements into the FE modelling process within the scope of the analysed LRB geometry, ISO-834 fire durations, and adopted material and modelling assumptions. Neglecting any of these components could underestimate the actual temperature distribution within the isolator and lead to significantly more critical results than anticipated under fire exposure.

The present study has several limitations that should be considered when interpreting the results. First, direct experimental validation of the numerical results is not included in this paper. Ongoing experimental studies are being conducted by the authors to investigate the fire exposure and post-fire mechanical behaviour of lead–rubber bearings. In future work, the experimentally obtained temperature histories and force–displacement responses will be used to validate and further refine the numerical modelling approach adopted in this study. Second, the thermal properties of rubber, steel, concrete, and lead were assumed to be temperature-independent. This simplifying assumption was adopted to maintain a controlled comparison among the analysed model configurations and is consistent with previous numerical studies; however, it may affect the accuracy of the predicted temperature field. Third, the thermo-mechanical procedure was performed using a one-way sequential approach, in which the thermal results were transferred to the mechanical analysis without feedback from mechanical deformation to the thermal field. Furthermore, the residual material model did not explicitly account for detailed thermochemical degradation mechanisms, rubber–steel debonding, thermal contact resistance, interface deterioration, permanent geometric distortion, or local damage to steel shims and flange connections. The bonded-interface assumption was adopted throughout the model. Finally, the analyses were limited to selected ISO-834 fire durations, one lead–rubber bearing geometry, and a mechanical loading protocol consisting of a vertical compressive stress of 10 MPa and a lateral displacement corresponding to 100% shear strain. The system-level response of the isolated structure was not analysed. Therefore, the results should be interpreted as a

comparative component-level numerical assessment rather than as a direct criterion for inspection, continued use, or replacement of fire-exposed bearings.

Declarations

Conflict of interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Author contributions

All authors contributed equally to this study. All authors have read and approved the final manuscript and accept equal responsibility for its content.

Data availability statement

The data presented in this study are available on request from the corresponding author.

Use of generative AI and AI-assisted technologies

The author(s) confirm the author(s) did not use any AI tools in the preparation of this work/research/study.

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