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Steel Ladle Linings—Key Issues Regarding Thermomechanical Behaviour

The steel ladle lining system has been selected as a typical example to illustrate the key issues regarding thermomechanical behaviour in high-temperature industrial processes. To enhance understanding of thermomechanical failure in general, in the introduction thermomechanical loads are classified into two categories according to whether or not thermal expansion is restricted externally. Subsequently, the influence of preheating as a decisive factor regarding the impact of thermal shock on different lining configurations with and without insulation is described. Finally, the reasons for joint opening and the occurrence of vertical cracks are discussed, which include irreversible strain in the refractory material and radial expansion of the steel shell.

Introduction

Material expansion with increasing temperature is a law of nature and valid for most refractories. While thermal expansion itself is not a problem, stresses occur if expansion is impeded. The restriction may originate from the refractory itself due to a temperature gradient or from the steel construction. Therefore two categories of thermomechanical failure can be distinguished: Damage due to high temperature gradients (self-restriction; type A) and damage resulting from thermal expansion in combination with an external mechanical constraint (type B). In the first example described below, thermal shock of an unconstrained refractory brick is considered, while the second case discusses mechanical restriction.
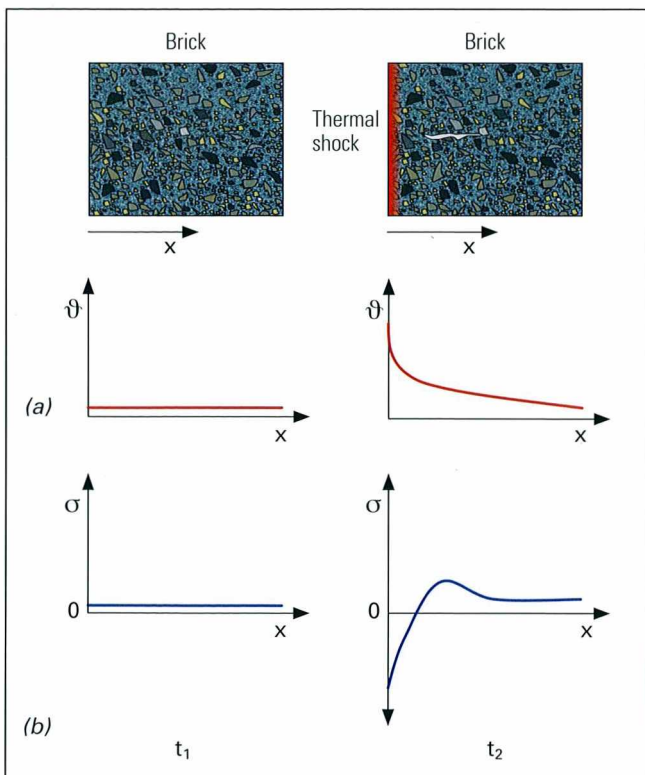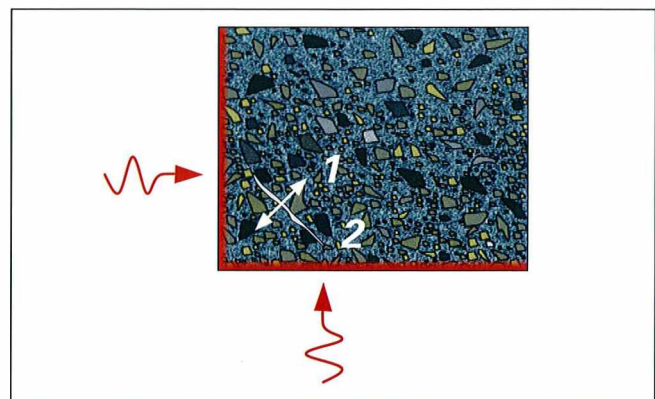
Temperature gradients cause stress gradients inside a brick. Principally, the two cases of cold and hot thermal shock can occur. The temperature and stress gradients through a brick are shown in Figure 1 for the case of a hot shock on one face of an isothermal brick. In the absence of external constraints, the brick expands and equilibrium is reached between the tensile and compressive stresses inside the brick. After a hot thermal shock, compressive stresses are observed directly at the hot face and tensile stresses appear some distance from the hot face. With further heat flux, the transition zone between compressive and tensile stresses moves towards the cold face. A typical failure mode associated with hot shock is formation of an internal crack perpendicular to the hot face. In the case where free edges in linings are subjected to a hot thermal shock, spalling of the edge is possible (Figure 2). The highest principal stress appears at 45° to both faces and the crack propagates perpendicular to the direction of the highest principal stress.

A cold thermal shock induces tensile stresses at the hot face and compressive stresses inside the brick. Similar to hot shock, the transition zone between compression and tension moves towards the cold face over the course of time.

As a result of globally restricted thermal expansion, compressive and shear failure may occur (type B). In this case large sections of the lining are under compressive loads

Figure 1. Graphic representation of (a) temperature and (b) stresses through a brick extending from the hot face before (t_1) and after a hot thermal shock in an unconstrained brick (type A). Time t_2 represents the moment of maximum tensile stress in the brick.

Figure 2. Schematic representation of thermal shock acting on an edge. The direction of maximum principal stress (1) and crack formation (2) are indicated.

(Figure 3) and compressive failure or creep results in irreversible compressive strains. Subsequently during cooling, joints between the bricks may open. In the course of further temperature increases, for example hot shock, tensile stresses may occur some distance from the hot face. Due to free expansion this corresponds to type A failure. A typically example of this situation is a poorly preheated lining with a low expansion allowance. During the first heat the steel shell is relatively cold and its thermal expansion is low. Since failure of the steel shell is rarely possible, in most cases the lining shows irreversible compressive failure strains. After cooling and the beginning of the next heat, prestressing is low and the probability of tensile failure is high. This shows that type B failure can facilitate type A; therefore, irreversible compressive stresses should be kept to a minimum. It also illustrates that closed joints during service can prevent tensile failure and premature wear. Furthermore in the case of thermal shock (type A), refractory shapes and the preheating schedule have a high impact on maximum stresses and must be considered for the lining design.

Influence of Preheating on Maximum Stresses

As previously mentioned, preheating has a significant impact on thermomechanical loads during initial heats. Firstly, the temperature gradient in the wear lining during thermal shock is decreased, thereby possible tensile stresses behind the hot face are reduced. Secondly, open joints between the bricks, introduced as expansion allowances, close during preheating. Furthermore, preheating increases both the lining temperature and steel shell temperature. The resulting thermal expansion of the steel shell generates an additional expansion allowance for the lining. Therefore, it is useful to calculate maximum stresses at the end of preheating and after thermal shock to determine appropriate preheating times.
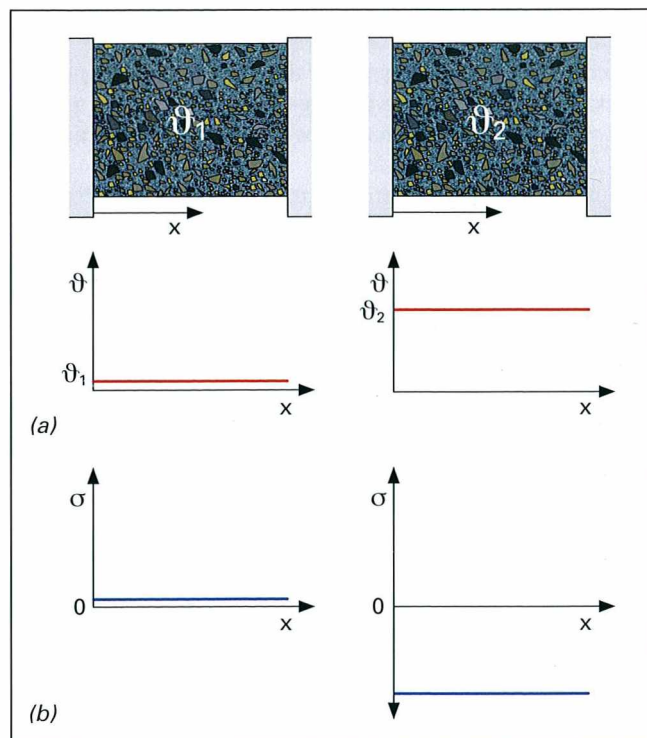

Figure 3. *Graphic representation of (a) temperature and (b) stresses for homogeneous temperatures $\vartheta_1 < \vartheta_2$ in a brick where thermal expansion is totally restricted (type B).*

Thermomechanical Simulation

A MgO-C lined steel ladle was selected for the following thermomechanical analyses. The wear lining thicknesses were 150 and 200 mm, and the permanent lining thickness was 65 mm. Two values (i.e., 7 W/mK and 11 W/mK) were considered for the wear lining thermal conductivity. The lining configurations were also simulated without and with insulation (i.e., 13 mm and 0.15 W/mK). The different wear lining thicknesses and conductivities are detailed in Table I.

A plane strain finite element (FE) model was established representing a symmetrical half of a wear lining brick, the corresponding permanent lining, insulation, and the steel shell (Figure 4). A rigid body was included to incorporate the joint space.

Stresses were simulated for a hot shock after 5, 15, 20, and 25 hour preheats and with no preheating. For all cases involving preheating, a hot face temperature of 1100 °C was achieved. A linear elastic material behaviour was assumed

Case	Conductivity (W/mK)	Wear lining thickness (mm)
1	11	200
2	11	150
3	7	200
4	7	150

Table I. *Wear lining thicknesses and conductivities examined in the case study.*
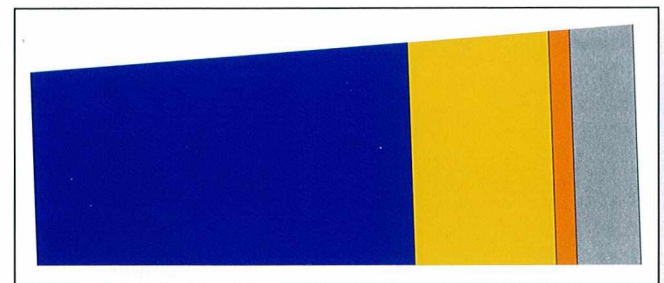

Figure 4. *The plane strain FE model geometry comprising the wear lining (blue), permanent lining (yellow), steel shell (grey), with or without insulation (orange) for the different cases in Table I.*
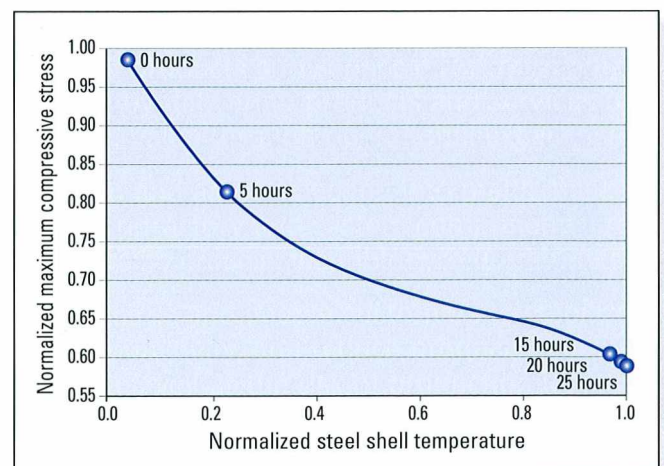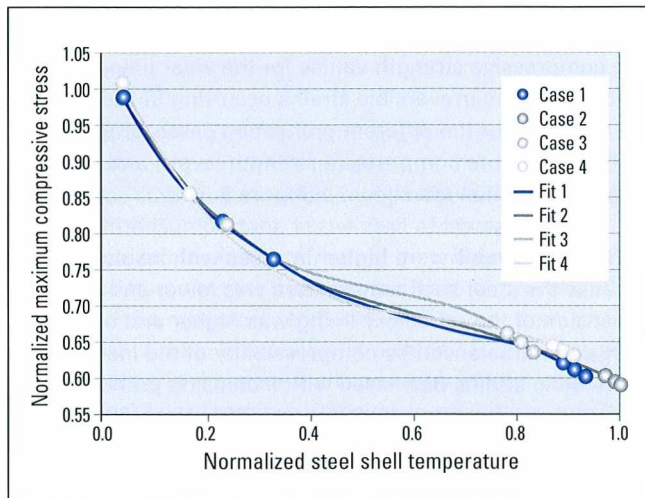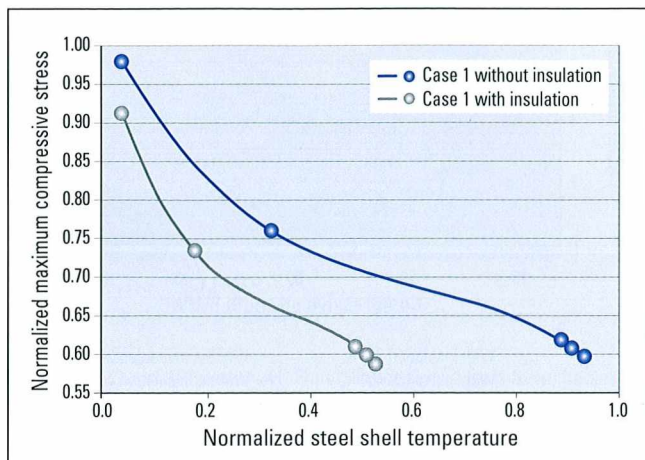

Figure 5. *Relationship between the normalized maximum compressive stresses in the wear lining after a hot shock and the normalized steel shell temperatures for case 2 without insulation, after different preheating times.*

for the case study. The maximum compressive stresses in the wear lining after thermal shock are plotted against the steel shell temperatures in Figure 5. The stresses and temperatures were normalized to the maximum values observed in all the simulated cases.

Generally, the compressive stresses decreased with increasing steel shell temperature, namely increased preheating time. For relatively short preheating times the stresses after thermal shock decreased significantly with further preheating. However, the additional benefit of preheating decreased with preheating time, since longer preheating cannot reduce the stresses further once steady state has been reached. For example, the stress reduction observed by increasing the preheating time from 15 to 25 hours was less than 5%. Preheating for 25 hours reduced the stresses by approximately 40% compared to the case without preheating. Variations in lining thermal conductivity and thickness caused only small differences between the four cases detailed in Table I for long and short preheating times (Figure 6). The relationship between the normalized maximum stress and normalized steel shell temperatures for cases 1–4 showed the highest level of scatter when the preheating time was 5 hours.

Figure 6. Relationship between the normalized maximum compressive stresses in the wear lining after a hot shock and the normalized steel shell temperatures for different preheating times and cases 1–4 without insulation.

Figure 7. Relationship between the normalized maximum compressive stress in the wear lining after a hot shock and the normalized steel shell temperature for different preheating times for case 1 with and without insulation.

The application of insulation was found to decrease the maximum compressive stresses occurring after a hot shock when there was no preheating and to a lesser extent when short preheating was used (Figure 7). For long preheating times the maximum compressive stresses were independent of insulation. The insulation decreased the steel shell temperature and increased the lining temperature when preheating was used and while both factors would increase stresses, the relatively high compliance of the insulation may have counterbalanced these effects.

Preheating influences both A and B type failure. Even if preheating does not increase the steel shell temperature, the temperature gradient at the hot face decreases and this reduces the probability of type A failure.

Reasons for Joint Opening

During service a heat flux usually appears in the radial direction. This means the temperature decreases from the hot face to the steel shell. As long as refractory materials behave in a linear elastic manner, no joint opening will occur during heating at the hot face. Compressive stresses in the wear lining and counterbalancing tensile stresses in the steel shell will be observed. However, if the stresses reach the compressive strength of the refractory material or if creep occurs, irreversible strains emerge. Initially this reduces the stresses but not the visible circumferential dimensions of the brick and therefore the lining appears closed. However during subsequent cooling, joints will open due to the irreversible strains that have occurred.

For joint opening to take place during heats, radial expansion of the steel shell after thermal shock is required. Results for radial displacement of the hot face and the steel shell for assumed linear elastic material behaviour can be seen in Figure 8.

The radial displacement during initial heats strongly depends on the preheating conditions. If preheating is sufficient, further radial displacement during the first heats may be small and the potential for joint opening is low [1]. Using results from simulations assuming linear elastic material behaviour a theoretical maximum irreversible strain $\varepsilon_{ir,max}$ can be calculated as follows and serves as an approximation for the joint opening after the ladle cools down:
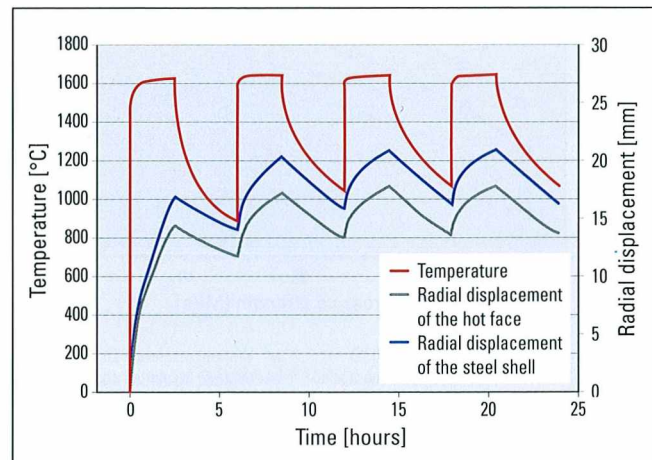
Figure 8. Temperature-dependent radial displacement of the hot face and steel shell.

$$\varepsilon_{ir,max} = \varepsilon_{th,R} - \frac{f_c}{E} \qquad (1)$$

Where $\varepsilon_{th,R}$ is the maximum thermal expansion of the refractory material. Residual elastic strain after compressive failure is calculated from the quotient of the refractory's compressive strength, f_c, and Young's modulus, E. The maximum irreversible strain was determined using thermal strain results from the previous studies; a value of 10 MPa was selected for the wear lining compressive strength. The influence of Young's modulus on the irreversible strain was found to be minimal (Table II).

In summary, potential reasons for joint opening are irreversible strain together with possible radial brick movement due to expansion of the steel shell and compressive stresses in a circumferential direction at the cold face of the wear lining brick. The thermal shock during ladle charging may cause irreversible strain as a result of both material failure and compressive creep. This may cause or increase joint opening after further equilibration during the same or subsequent heat: A higher thermal strain some distance from the hot face—whether in the wear lining, safety lining, or steel shell—reduces compressive stresses at the hot face and may cause joint opening after the compressive stresses have disappeared. Nevertheless, also in the case of joints that have already opened during the previous idle time, thermal shock may cause an irreversible strain due to compressive stresses at the hot face. In this case the colder areas of the brick act as the restriction. These colder regions are then exposed to tensile stresses and may also show mode I fracture.
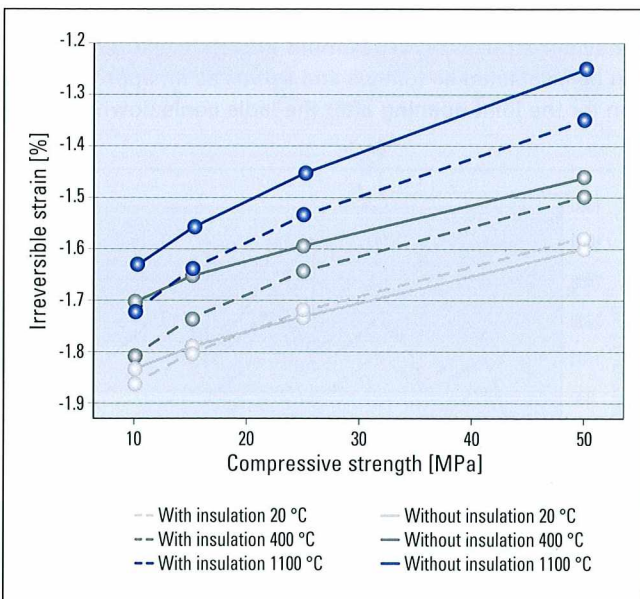
To simulate the irreversible strains in the FE model, the Mohr Coulomb plasticity model was applied to account for multiaxial loading. For refractories, the material strength typically increases with increasing hydrostatic pressure. In this model the material behaved in a linear elastic manner until the failure surface was reached. The failure surface can be described as:
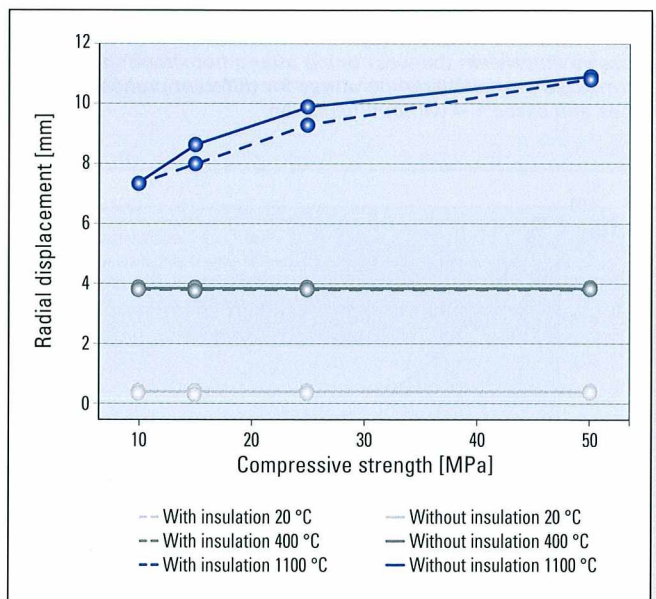
$$|\tau| = c - \sigma \tan\phi \qquad (2)$$

Where c is the cohesion, ϕ the friction angle, σ the normal stress, and τ the shear stress. Usually the cohesion and friction angle are determined from triaxial compression tests. For high-temperature measurements this can be performed using the so-called modified shear test [2]. In the following study, material behaviour was described considering temperature-dependent cohesion. For pure uniaxial compressive stress the cohesion can be calculated from:

$$c = f_c \frac{1 - \sin\phi}{2\cos\phi} \qquad (3)$$

The uniaxial compressive strength is represented by f_c. For a small friction angle the cohesion is close to half the compressive strength. In this study, the friction angle was set at zero to limit the compressive stresses to twice the cohesion. The compressive strength values for the wear lining were 10–50 MPa. The irreversible strains occurring at the end of the first heat for the different preheating cases, at various high-temperature compressive strength levels, and with and without insulation are shown in Figure 9.

Irreversible strains were higher in cases with insulation because the steel shell temperature was lower and thermal expansion of the refractory lining was higher and only partially counterbalanced by compressibility of the insulation. Irreversible strains decreased with increasing preheating temperature. The main reason was radial expansion of the outer shell during preheating (Figure 10).

	Multiplication factor for Young's modulus		
	1/2	1	2
$\varepsilon_{ir,max}$	1.90%	1.92%	1.93%

Table II. Maximum irreversible strain for a wear lining with a hot compressive strength of 10 MPa.

Figure 9. Relationship between irreversible strain in the circumferential direction at the end of the first heat and the compressive strength of the wear lining for a lining configuration with and without insulation. The conditions examined were no preheating and preheating to 400 °C or 1100 °C.

Figure 10. Relationship between radial displacement of the steel shell prior to the first heat and compressive strength of the wear lining for a lining configuration with and without insulation. The conditions examined were no preheating and preheating to 400 °C or 1100 °C.

Reasons for Vertical Cracking

From the aforementioned findings, the following scenario is a probable explanation for the case of vertical cracking in steel ladle wear lining bricks [3]:

>> Compressive stresses at the hot face are generated when a relatively cold ladle is used in the steel plant. This can lead to compressive failure; this type of failure corresponds to type B failure. Further heating of the ladle leads to joint opening at the hot face due to irreversible strain and radial brick displacement. In the case of cyclic ladle use, the joints act as an expansion allowance. Since compressive stresses are absent, a hot shock may cause cracking due to tensile stresses.
>> The compressive failure in a circumferential direction is significantly higher than in a vertical direction because expansion in a vertical direction is less restricted [3]. Therefore, in some cases bricks with smaller dimensions in a circumferential direction can be advantageous due to the higher number of joints.
>> Rapid cooling at the hot face may cause crack formation in a radial direction, even without prior compressive failure (type A).
>> Due to compressibility of the insulation or permanent lining, the inner ladle circumference may increase; this would result in vertical joint opening at the hot face.

Conclusion

Besides preheating, occasionally applied insulation has a considerable impact on the temperature distribution and final stress state in a steel ladle. In particular, the steel shell temperature is important. In the case of insulated ladles, irreversible strains in the refractory materials increase. This originates from the fact that the steel shell temperature is lower and the refractory temperature is higher than in the noninsulated case. Irreversible strains and further temperature elevation in the steel shell can result in joint opening and vertical brick cracking. However, even if it appears that a lining configuration without insulation is beneficial in terms of thermomechanical behaviour, insulation may be applied to improve the energy balance.

A creep model, in particular for the wear lining, may further improve the significance of results due to the incorporation of time-dependent material behaviour. These investigations are topics of ongoing research projects.

References

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