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Estimation of Thermal Stress Generated in Bricks under Restraint and Its Application in Brick Joint Design

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要 旨

耐火物ライニングの設計において、れんがの亀裂、剥離は対策の優先度の高い損傷である。本研究では実炉に即した条件でのせり割れの再現実験、および熱応力の解析を行った。実験および解析結果から、アルミナ質れんがにおける熱応力は、クリープの影響は小さく熱間の弾性率が支配的であることが示された。

Abstract

In order to prevent cracking and peeling damage in relined refractory bricks which are restrained by neighboring bricks and furnace steel shell, brick joint design is quite important so as to regulate generated thermal stress in the proper range in overall brick relining design work. To experimentally reproduce joint damage under similar restraint conditions to a practical furnace, heating tests were conducted on two types of alumina bricks tightly relined in the test furnace, and the heating test results were verified with FEM analysis. It was concluded that the degree of compressed stress generated in restrained bricks is dominantly influenced by the modulus of elasticity with less influence by the creeping deformation which contributes to stress relaxation.

1. 緒言

耐火れんがは各種窯炉での稼働において高温にさらされ、その損傷形態は多岐にわたる¹⁾。その中で、亀裂や剥離は、進行が急激で耐用への影響が大きく、対策の優先度が高い。亀裂、剥離の原因はさまざま、実炉においては複数の原因が複合的に関係しており、その一つとして、熱膨張による応力が挙げられる²⁻¹²⁾。実炉構造体において、れんがは他の耐火物や鉄皮によって拘束された状態であり、加熱された際に熱膨張による変形が抑制されることで、せり応力が発生する。この応力による亀裂損傷はせり割れと呼ばれ、稼働面側の目地部が先行的に欠けるピンチングが損傷形態として知られている(Fig.1²⁾)。また、応力が大きい場合には損傷が大きくなり、広範囲な亀裂、剥離につながるため、応力を十分に緩和し、せり割れを抑制することがライニングの設計において重要となる。応力緩和の代表

1. Introduction

Refractory bricks relined in furnaces are damaged with complex causes as they are exposed to elevated temperatures in operation¹⁾. Since cracking and peeling-off damages extend more rapidly than other types of damage, their influences on overall refractory durability are so serious and marked that prompt preventive measures need to be taken. Cracking and peeling-off damages are caused by many factors which can be correlated compositely in practical operation. Stress generated by thermal expansion of refractory brick has been cited as one of the important factors²⁻¹²⁾. Relined refractory bricks are usually restrained by other neighboring refractory

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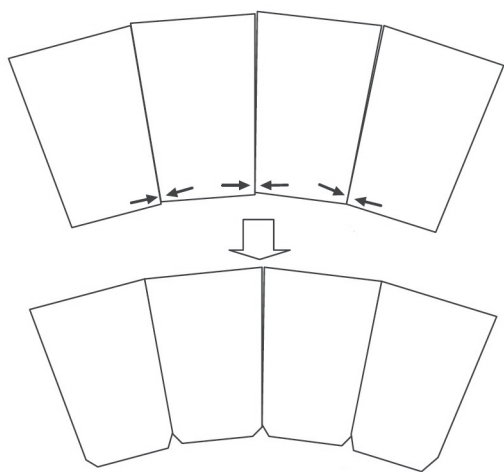
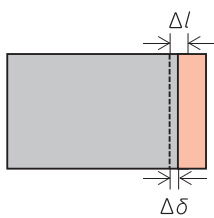
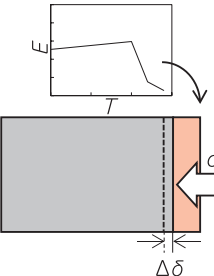
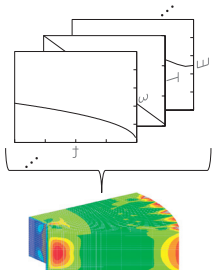


Fig. 1 Schematic illustration of pinching damage at brick joints.

bricks and furnace steel shell in a practical lining structure in furnaces. When heated up, deformation induced by thermal expansion is suppressed because of physical restraint on the refractory bricks, resulting in generation of compressive stress in the brick body. It is well acknowledged that, as schematically illustrated in Fig. 1²⁾, the edge portions of the heating face of heated-up bricks conflict intensely with each other by compressive stress in the brick bodies, resulting in fracture of edge portions, namely, pinching damage. Such damage occurring specifically at the brick joint portion and other types of cracking damages induced directly or indirectly by compressive stress generated in restrained refractory bricks are collectively referred to as joint damage in this report. When compressive

Table 1 Comparison of Estimation methods on generated compressive stress or damage caused by thermal stress

	(a) Conventional model	(b) Simple model with material properties	(c) FEM simulation
Schematic			
	Comparing length of brick expansion and structural deformation.	Calculate thermal stress and compare with strength.	Calculate thermal stress distribution and variation with properties and operation data.
Required data	Thermal expansion, Mortar compressibility, Dimensions.	Thermal expansion, Mortar compressibility, Elasticity, Dimensions.	Thermal expansion, Mortar compressibility, Elasticity, Creep deformation, Thermal conductivity, Heat capacity, Temperature history, Kiln structure, Etc. ...
Feature	Low calculation cost. Fewer data needed.	Sufficient accuracy. Practical required data.	High precision. Applicable to any situation (theoretically).
Defect	Low resolution. Depend on empirical criterion.	Limited circumstances require.	High cost for calculation and data correction.

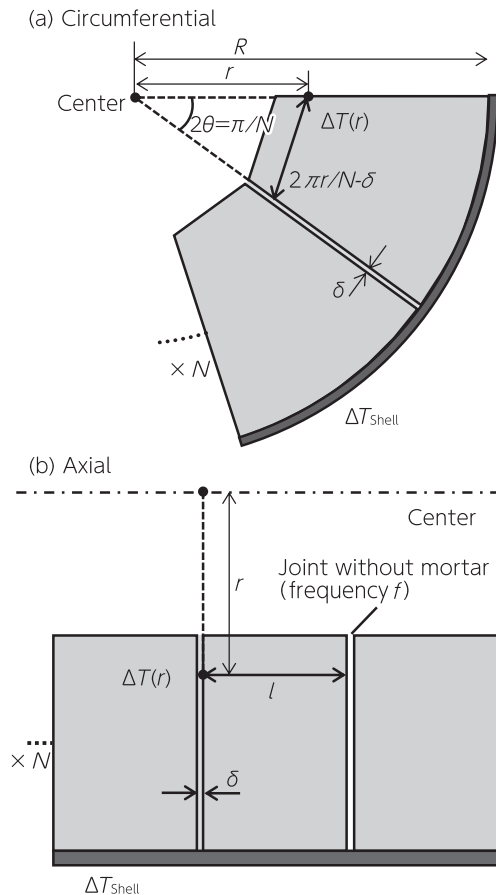


Fig. 2 Schematic illustration of simple model for calculating compressive stress; (a) circumferential direction, (b) axial direction.

的な手法として、目地の導入が挙げられる。目地の設計には、目地の幅や目地材の特性によって適切な応力緩和能を与えることが求められる。旧来、目地の設計は経験則に依存しており、熱応力を精度よく見積もること³⁻¹³⁾、より効果的な設計を行うことが可能となる(Table 1)。発生応力を実験的に測定する方法として、試料を一軸で拘束し、加熱する手法が報告されている⁴⁻⁷⁾。発生応力を直接得られるが、実炉とは拘束の条件が異なるため、実炉評価への適用には検討を要する。また、発生応力を数値的に見積もる方法として、膨張率と緩和率の差から熱ひずみを計算する方法が挙げられる。計算モデルをFig.2, 式1, 2に例示する。この方法は、1次元の線形モデルで、れんがの軟化などの非線形挙動を考慮しないが、簡便に設計の目安を得ることができる。

stress generated in the brick body is large, the magnitude of joint damage becomes severe and can induce cracking or peeling-off damages in the affected region. Therefore, sufficient relaxation of generated stress is an important issue for suppressing or preventing joint damages in relining design work. One of the typical methods used to relax generated compressive stress in brick bodies is the incorporation of suitable brick joints. The design work of such joints needs to be elaborated so as to implement appropriate stress relaxation while taking into account joint width or characteristics of filling materials in the brick joints. As indicated in Table 1, design work on the brick joints, which has conventionally relied on empirical rule, can be efficiently conducted by precise estimation of generated compressive stress or damages caused by thermal stress in the brick body³⁻¹³⁾. Experiments in which, the stress generated in a brick body by heating up the brick sample restrained in the uniaxial direction, was measured have been reported⁴⁻⁷⁾. Even though generated stress was obtained directly in such experiments, its adoption for brick joint design work on practical furnace relining structures should be carefully examined because of the differences in restraining conditions. A numerical model in which thermal strain was calculated with using the difference between thermal expansion rate and stress relaxation rate is cited as a quantitative estimation on generated stress. A schematic illustration of such calculation model is shown in Fig. 2, and the calculation equations are shown in equations (1) and (2). This calculation model, a one-dimensional linear model in which nonlinear events, such as softening behavior of brick, are not considered, can be used to easily provide guidelines for brick joint design work.

$$\sigma_{\text{circ}}(r, T) = E(\Delta T(r, T)) \cdot \left(\Delta T(r, T) \cdot \alpha_{\text{brick}} - \left(\alpha_{\text{shell}} \cdot \Delta T_{\text{shell}}(T) + \frac{\delta \cdot s}{\frac{2\pi \cdot r}{N} - \delta} \right) \right) \cdot \cos \frac{\pi}{N} \quad \dots\dots (1)$$

$$\sigma_{\text{axis}}(r, T) = E(\Delta T(r, T)) \cdot \left(\Delta T(r) \cdot \alpha_{\text{brick}} - \left(\alpha_{\text{shell}} \cdot \Delta T_{\text{shell}}(T) + \delta \cdot \frac{(1-f) \cdot s + f}{l} \right) \right) \quad \dots\dots\dots (2)$$

T	: Inner temperature
r	: Distance from center of surface
$\sigma_{\text{circ}}(r, T)$	: Thermal stress in circumferential direction
$\sigma_{\text{axis}}(r, T)$	: Thermal stress in axial direction
$E(\Delta T)$	: Modulus of elasticity (MoE)
$\Delta T(r, T)$	: Temperature change from R.T.
α_{brick}	: Coefficient of thermal expansion of brick
α_{shell}	: Coefficient of thermal expansion of steel shell
$\Delta T_{\text{shell}}(T)$	: Temperature change from R.T. in steel shell
δ	: Joint width
s	: Compressibility of joint material
N	: Number of bricks in circumferential direction
l	: Brick length in axial direction
f	: Frequency of dry joint with no joint material

また、詳細な材料特性や温度経過、炉構造を考慮して応力を求め、亀裂の発生を推定するため、有限要素法 (FEM) に代表されるコンピューターシミュレーションを活用する検討がなされている⁸⁻¹²⁾。相応の計算コストを要するが、発生が予想される亀裂の位置や方向、発生時期などの詳細を推定することが期待できる。本研究では、せり割れを実炉に近い条件で再現する実験と、その結果のFEM解析を行った。材質による亀裂傾向の違いと、損傷に影響する要因について報告する。

2. 試験方法

2.1 試験炉による拘束下加熱試験

実炉に近い条件でのせり割れ再現試験を目的として、試験炉による実験を行った。Fig.3に装置外観を示す。試料れんがは1周10枚として、円周状に施工し、れんが間の目地を小さく管理することで、円周方向を強く拘束した。目地は隙間ゲージを用いて、幅0.2mm未満となるように管理した。加熱試験では、れんが内面をヒーターで1500℃まで4℃・min⁻¹で加熱した。鉄皮は水冷して30℃に管理し、鉄皮の変形を抑えた。

試料として、汎用のアルミナ質れんが2種を供した。代表品質をTable 2に示す。れんがAはアルミナ値が高く、耐食性等、化学的特性を重視したれんが、れんがBはより機械的特性を重視した設計のれんがである。両れんがの差異として、熱間特性が挙げられる。弾性率をFig.4、クリープ変形をFig.5に示す。れんがBは、弾性率がれんがAと比較して小さく、またクリープ変形が大きいことで発生応力の低減、緩和が期待される。

2.2 FEM解析による応力計算

実験における亀裂と応力、材料特性について検証するため、FEMによる応力シミュレーションを行った。使用モ

For more sophisticated estimation, the computer simulation representative finite element method (FEM) computing technique can be exploited⁸⁻¹²⁾. Generated stress is numerically calculated referring to characteristics of refractory bricks, temperature changes and lining structures so as to evaluate probability of crack initiation in the computer simulation works. Even though such computer simulation work requires commensurate calculation cost, the timing and location of crack initiation, as well as its extending direction can be estimated with reasonable precision in return.

A series of experiments in which joint damages are reproduced under similar restraint conditions in practical lining structure were conducted, and the obtained results of experiments were evaluated with FEM analysis. The influences of the characteristics of refractory bricks on joint damage patterns and influencing factors on joint damages are described in this article while considering details of experiments and numerical analysis.

2. Experiment

2.1 Heating test of refractory bricks under restraint

A heating test was conducted with refractory bricks relined in test furnace to experimentally reproducing joint damage under similar restraint conditions to those of practical furnaces. As shown in Fig. 3, 10 of



Fig. 3 Appearance of refractory bricks relined in test furnace.

Table 2 Major specifications of sample bricks

	Brick A	Brick B
Al ₂ O ₃ content / %	99	90
Apparent porosity / %	18.0	16.0
Bulk density / kg·m ⁻³	3.3·10 ³	3.0·10 ³
Crushing strength at R. T. / MPa	88.0	98.0
Thermal expansion at 1000 °C / %	0.80	0.60

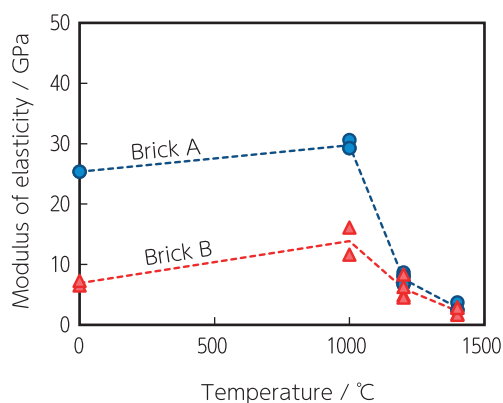


Fig. 4 Modulus of elasticity of sample bricks at various temperatures.

デルをFig.6に示す。モデルでは、1/2のれんが2つを作成した。応力にかかる材料特性として熱膨張係数、熱間弾性率、およびクリープ変形を与えた。計算結果は最小主応力によって評価し、材料特性の影響を検証した。

3. 結果と考察

3.1 試験炉による拘束下加熱試験

Fig.7に試験後の天端面、および加熱面を示す。れんがAは目地周辺を中心に亀裂が認められ、また、一部加熱面が剥離する損傷が認められた。一方で、れんがBでは有意な亀裂発生は認められなかった。目地部加熱面側の亀裂は進行することでピンチング損傷につながるものと考えられる。加熱面の剥離についてもれんが間のせりが原因と考え

refractory bricks were relined circumferentially in the test furnace. The brick samples were relined quite tightly with minimized joint width to be restrained in the circumferential direction. The bricks were tightly relined with less than 0.2 mm of joint width, which was secured with a thickness gauge. In the heating test, inner surface of the relined bricks was heated up to 1500 °C with 4 °C/min of heating rate by the heaters. During the heating test, the temperature of the test furnace steel shell was kept at 30 °C by water cooling so as to suppress deformation.

Two types of general-purpose alumina brick were used for the heating test. Major specifications of the sample bricks are summarized in Table 2. Alumina brick A, with high alumina content, is characterized by superior chemical characteristics such as corrosion resistance. Alumina brick B was designed with the intention to secure its physical properties. The noteworthy difference between the two types of brick is their mechanical characteristics at elevated temperatures. The modulus of elasticity (MoE) is compared between brick A and brick B at various temperatures in Fig. 4. Creep deformation is compared between brick A and brick B under various conditions in Fig. 5. Since, in comparison with brick A, brick B exhibits smaller MoE and higher creep deformability, better stress relaxation in brick B is expected.

2.2 Stress calculation by FEM analysis

FEM analysis was carried out to analyze the relation among the heating test results such as magnitude and location of initiated joint damages, the stress expected to be generated in the sample bricks, and the physical properties of the sample bricks. As shown in Fig. 6, in which the FEM analysis model is illustrated, two pieces of half of the sample bricks were modeled. Thermal expansion coefficient, MoE and creep deformation were taken into account as physical properties of the bricks, which influence generated stress and its relaxation. The FEM analysis results were evaluated by calculated minimum principal stress and the influences of the physical characteristics of the brick on minimum principal stress were examined.

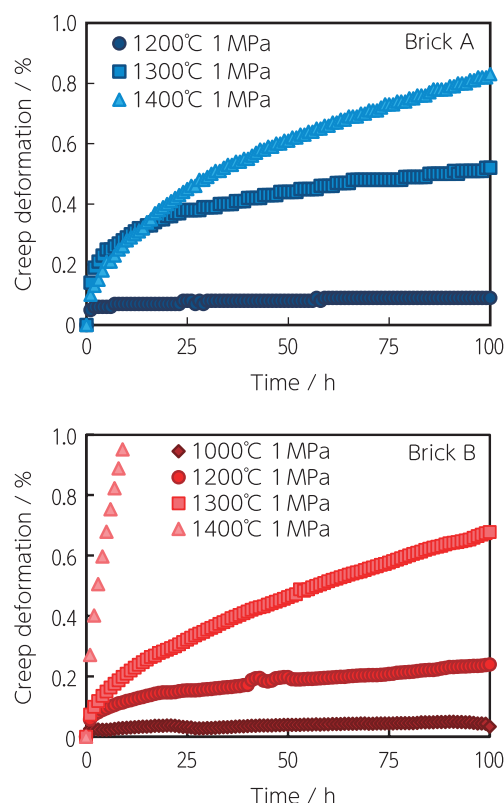


Fig. 5 Creep deformation of sample bricks at various temperature.

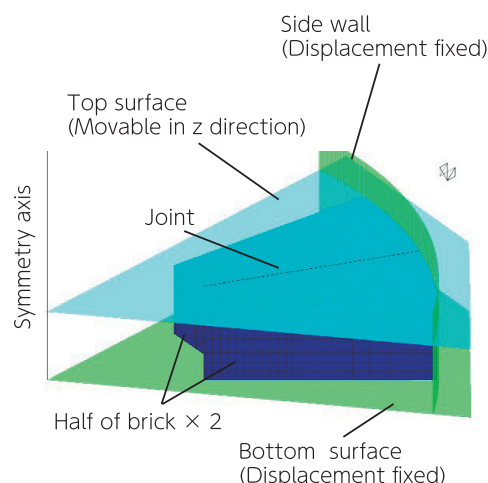


Fig. 6 Model for FEM analysis.

られ、迫割れの再現ができたものとする。また、れんがAおよびBで亀裂の発生に差がみられ、材質による傾向の違いを再現することができた。

3. 2 FEMシミュレーションによる実験結果の検証

Fig.8に試験炉のFEMシミュレーションによる、1000°Cにおける最小主応力分布を示す。加熱面近傍に応力の発生が認められ、特に、目地部に強い応力が集中していた。最小主応力は負の値を示し、せり応力に相当するといえる。また、背面側の応力発生位置は鉄皮との接触位置に相当す

3. Results and Discussion

3. 1 Heating test of refractory bricks under restraint

The top surfaces and heating surfaces of two types of alumina bricks after a heating test under restraint in the test furnace are comparatively shown in Fig. 7. Cracks were observed at the vicinity of the brick joints on the top surfaces of brick A along with peeling damages on some heating surfaces. No significant crack was observable in brick B. It is inferred that further progression of cracking at the vicinity of the brick joint on the heating surfaces would lead to pinching damage. It was also inferred that peeling damages on some heating surfaces of brick A were induced by compressive stress generated in the brick body. In short, experimental reproduction of joint damages was successfully performed.

3. 2 Verification of heating test results with FEM analysis

As one of the FEM analysis calculation results, the distribution of the minimum principal stress in brick A and brick B at 1000°C are comparatively shown in Fig. 8. Intensive stress was generated near the heated surface in association with sharp stress concentration at the brick joints in both brick A and brick B. The location of the generated stress at the back face corresponds to the contact point between brick and the test furnace steel shell. Despite a similar pattern of distribution of minimum principal stress, the intensity of the generated stress in brick A was much bigger than that in brick B. This verified the differences in the degree of initiated damages in the two types of bricks in the heating test.

A series of FEM analysis simulations are conducted with varying MoE based on FEM analysis on brick A to evaluate the degree that the physical properties have the intensity of generated stress. The influence of MoE on minimum principal stress is shown in Fig. 9. The stress showed negative value and the absolute value corresponded to the compressive stress. In accordance with the lowering of MoE, the compressive stress was lowered. At around 0.4 times the MoE of brick A, the compressive stress

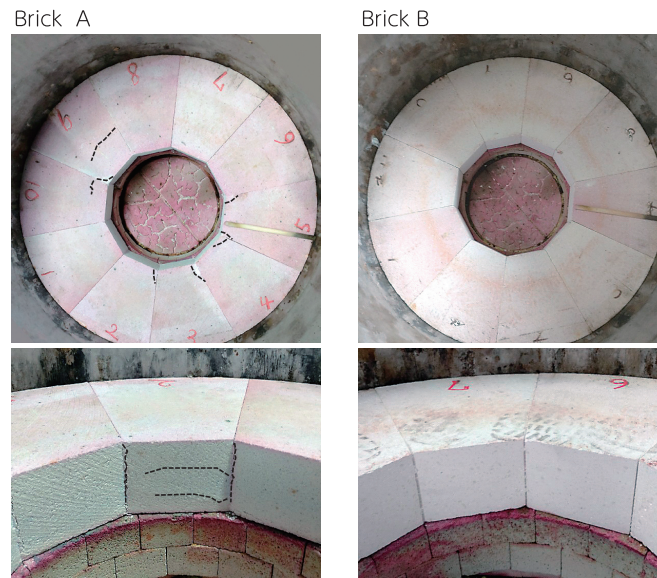


Fig. 7 Appearance of top surface and heating surface of sample bricks after heating test.

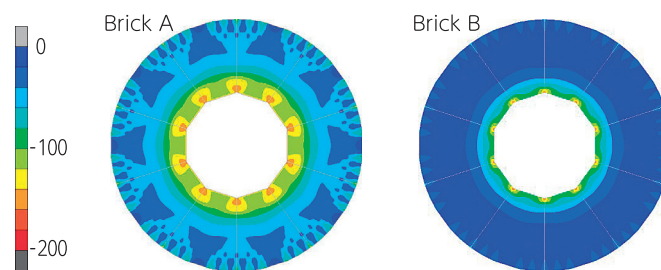


Fig. 8 Minimum principal stress distribution calculated by FEM analysis.

る。れんがAとBで応力の分布は同様であったが、大きさには差が認められ、れんがAの方が大きな応力が発生しており、実験における亀裂傾向の差が再現できたと考える。材料特性の影響を検証するため、れんがAのモデルをもとに、弾性率を定数倍した場合のFEMシミュレーションを行った。加熱面目地部の最小主応力変化をFig.9に示す。弾性率が小さくなると応力の絶対値は小さくなり、弾性率が0.4倍で、れんがBの結果と同等になった。0.4倍の弾性率はれんがBの弾性率とほぼ一致し、今回の実験において、発生応力は弾性率が支配的であったと示唆された。アルミナ質のれんがAとBでクリープ量に差はあるものの、変形量は小さく、れんがの軟化による応力緩和は影響が小さかったものと考えられる。一方で、粘土質れんがなど軟化の影響の大きい材質系の場合、クリープ変形などれんが自身の応力緩和の影響が大きくなることが考えられる。れんがBよりも軟化の大きい材料の場合は非線形挙動を考慮したモデルでの検証が必要であると考えられる。また、耐火物の弾性率は温度に大きく依存するため、発生応力の推定には熱間弾性率の使用が必要であるといえる。

became almost the same value as that of brick B. It is inferred that, since 0.4 times the MoE of brick A coincides to that of brick B, the generated stress was dominantly influenced by MoE. Despite difference in creep deformation between the two types of brick, the actual deformation of the bricks was not significant, and the influence of the softening of the brick on stress relaxation was not so marked in the case of this study. It is inferred that in the case of bricks which are characterized by high deformability by softening, for example, fireclay refractory bricks, the influence of stress relaxation caused by deformability of brick, such as creep deformation, on generated compressive stress would be prominent. It was thought that, when joint damage in refractory bricks with deformability larger than that of brick examined B, nonlinear behaviors of the brick need to be taken into account. It was noted that, because

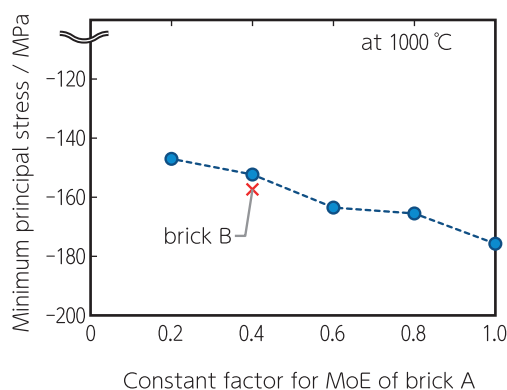


Fig. 9 Influence of variance in modulus of elasticity on minimum principal stress at 1000 °C.

4. 結言

アルミナ質レンがを用いた拘束下加熱実験および、その解析を行った。実炉を模した試験炉による実験により、レンがの迫割れを再現する結果が得られた。また解析により、応力は約1000℃で最大となり、中間温度域での亀裂発生が示唆された。また、今回の条件では、亀裂の発生においてクリープの影響は小さく、熱間の弾性率が支配的であったものと考えられる。

of the high temperature dependency of MoE, MoE at elevated temperatures should be adopted for computer simulation work.

4. Conclusion

Heating tests were conducted on two types of alumina bricks which were tightly relined in the test furnace, namely, they were under physical restraint. FEM analysis was also conducted to analyze the heating test results. Joint damage was reproduced experimentally In the heating test under similar restraint conditions in practical furnaces. FEM analysis revealed that compressive stress generated by heating was maximized at roughly 1000 °C with indication that crack initiation took place in the intermediate temperature range. It was concluded that, in the heating test on alumina bricks, occurrence of joint damage is dominantly influenced by MoE with smaller influence of creeping deformation which would contribute to stress relaxation.

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