Investigating the structural contribution of patch repairs to reinforced concrete elements

Vafa Naraghi*, *Nicholas* Jarratt, and *Hans* Beushausen+

Concrete Materials and Structural Integrity Research Unit, Department of Civil Engineering, University of Cape Town, South Africa

Abstract. The patch repair method is one of the most common approaches used by engineers for repairing reinforced concrete structures that have been damaged. Despite its popularity, the knowledge on material properties pertinent to a durable structural repair is still lacking. Most standards and guidelines on concrete repair currently specify arbitrary limits when it comes to the properties of repair materials. In the case of structural patch repairs, these arbitrary limits have led to the development of high-strength cementitious repair mortars, often marketed as "high-performance", that are tailored to meet the specifications and not the needs on-site. The paper discussed here forms part of a greater study that aims to increase the understanding of patch repairs and inform existing guidelines on designing structural patch repairs. Three commercially available high strength cement-based repair materials were tested for their strength, elastic modulus, shrinkage, and creep properties. These properties were then used as inputs to an analytical model that was developed to determine the distribution of stress in a repaired element over-time. The results from the analytical model suggest that high strength materials do not structurally contribute in the long term, for patch repaired concrete elements under axial compression.

1 Introduction

The repair and rehabilitation of RC structures has become a common requirement in modern construction [1]. The most significant cause of deterioration in RC structures is the corrosion of steel reinforcement [2]. In the repair of such RC structures, often part of the concrete requires restoration. Concrete patch repair techniques are commonly used in such restoration applications.1`

Concrete patch repairs are broadly categorised into structural and cosmetic repairs. Structural patch repairs are expected to carry loads or stresses and contribute to load sharing in the repaired concrete element.

A study by Tilly & Jacobs [3] found that most concrete repairs fail within the first 5 years of the repair. These failures have largely been attributed to inappropriate repair design and inappropriate repair material choice. Existing codes and guidelines for concrete repair provide a framework for concrete repair design, implementation, and management. While these frameworks are sufficient to guide concrete repairs conceptually, they are limited in providing measurable guidance on repair material selection to designers and applicators.

In cases where guidance is given, the performance criteria specified is either arbitrary, with little justification, or stems from design codes for new concrete structures, which are not representative of concrete repairs. There is, thus, a need to develop appropriate tools and guidelines for selecting structural repair mortars.

Numerous publications have discussed the effects of property mismatch and incompatibility between the repair material and parent concrete [4–8].

For a repair to be durable, the properties of the repair material must ensure that the repair system can withstand the stresses induced by intrinsic and extrinsic effects without distress or deterioration [9], which can vary depending on the principle function of the repair.

For structural patch repairs, the most significant material properties are the elastic modulus, shrinkage, and creep. Other properties such as compressive and tensile strength, Poisson's ratio and coefficient of thermal expansion or contraction have secondary effects on the performance of such repairs. Numerous proprietary repair materials have been developed and continue to be developed for structural patch repair applications, with the above material properties in mind. Among such are high strength cementitious grouts, which, in South Africa, are often preferred for structural patch repair applications based on their reported material properties. However, the reported properties in these product data sheets are mostly insufficient in determining the performance of the structural repair over time.

Empirical studies have been conducted to assess the performance of repaired axially loaded RC elements. Some studies focused on the repair geometry, while others focused more on the repair material properties. In these studies, RC columns with a square cross-section were considered. Pellegrino et al. [10] investigated the ultimate load bearing capacity of repaired RC columns having different repair thicknesses on one side, while Ortega et al. [11] considered columns that were repaired

* Corresponding author: nrgvaf001@myuct.ac.za
+ Corresponding author: hans.beushausen@uct.ac.za

on one and all-four sides of the square column, with a constant repair thickness. The results showed that if the repair is to contribute to the axial load bearing capacity of the member, the depth of the repair needs to be such that the steel reinforcement is encapsulated, while an increase in the repair area reduces the repaired members load bearing capacity.

In the case of the repair material properties, particular focus has been placed on the elastic modulus. Da Porto et al. [12], who repaired all four sides of a square RC column, considered three different polymer-modified repair mortars, each having different modulus of elasticity values. An elastic modulus of 9-10 GPa was used by Kristiawan et al. [13] to investigate patch repaired RC columns under eccentric compressive loads. In the study by Ortega et al., the columns repaired on either one [14] or all-four sides [15] was done using class R3 and R4 structural repair mortars, as defined by the European Standard EN 1504. Sharif et al. [16] investigated the structural effectiveness of patch repairs on RC columns using two materials that were described as having a "high" and "low" modulus of elasticity, respectively.

While these studies showed that the elastic modulus does affect the ultimate axial load bearing capacity of the repaired RC member, they do not consider the repairs long-term performance under normal service conditions. Studies on time-dependent properties such as shrinkage and creep, and their impact on the axial load bearing capacity of repaired RC members are limited. The most notable study is that by Shambira & Nounu [17], who measured the strain distribution in RC columns that were repaired with a polymer modified and polymer concrete and axially loaded over a 44-day period. They found that while the repair can contribute to the load-bearing capacity of the patch repaired RC column in the short-term, its contribution decreases over time. Furthermore, these reductions were shown to be higher when the repair materials shrinkage increased.

There is a dearth of research that considers the performance of the repair material, due to the varying effects of multiple repair material properties. There is also very little evidence in literature that cement-based repair mortars can contribute to the load bearing capacity of repaired axially loaded elements, under service conditions.

While few numerical models have been developed to describe the stress and strain behaviour and performance of structural concrete repairs, there exists no analytical model or tool that quickly determines the stress and strain behaviour of a structural patch repair over time.

This paper seeks to contribute towards the research on structural patch repairs and improve the understanding of repair material properties and its effects on structural patch repairs in concrete structures. In doing so, an analytical model is developed to investigate the distribution of stresses in a patch repaired element under axial compression. The paper is split into 3 parts. The first part is the intro, the second is the theory, which is then followed by the material inputs. Finally, the results of the model are presented, and the paper concluded.

2 Analytical model

The analytical model described here represents an analysis of the stresses and strains, within the linear elastic range of the materials, in a repaired element that is axially loaded. The primary purpose of the model is to establish to what extent repair materials contribute towards the load bearing capacity of patch repaired members under axial compression.

Since the stress and strain distribution in a repaired element is influenced by the material properties of the substrate concrete and repair material, and their interaction with the environment and imposed loading conditions, the model uses externally applied stresses and material property information as inputs, specifically the elastic modulus, shrinkage, and creep.

2.1. Model assumptions and limitations

The model was developed using Hooke's law and Euler-Bernoulli beam theory. Hooke's law was used to govern the distribution of the imposed axial stress in the repaired concrete element, while the strain deformations in the repaired element followed the two main assumptions made in the Euler-Bernoulli beam theory, which are that plane sections remain plane under stress and deformation angles in the beam are negligible.

The model only considers axial compressive stresses that are applied instantaneously and are assumed to act uniformly, with no load eccentricities. For the material properties, since this is a continuous phenomenon that occurs in cementitious materials, time step increments of 1 day were used to approximate the elastic modulus and the shrinkage and creep strains in the repair. Concrete repairs are typically conducted on aged concrete structures. Thus, the elastic modulus of the substrate concrete was assumed to be constant, along with the deformations from creep and shrinkage being negligible.

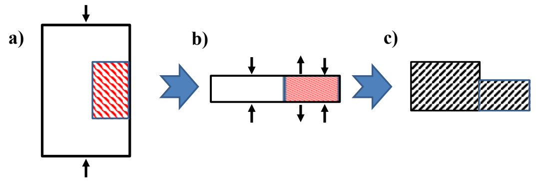
For simplicity, complete bond was assumed at the interface of the substrate concrete and repair material. This bond facilitates the complete transfer of stresses through the materials and allows the strains in both the substrate and repair material to be equal.

2.1.1 Repair material properties

The repair material properties in the model were based on experimental tests conducted in the labs. The elastic modulus of each repair material was assumed to have fully developed within the first 28 days and remained constant thereafter. As for shrinkage and creep, the free shrinkage strain and creep characteristics of the repair material was measured over the first 90 days, beyond which additional shrinkage and creep was not considered. A time-development estimate of the creep characteristics for each material was developed over the first 90 days to fit the measured data for each repair material.

2.2. Model theory and implementation

The model first considers the repaired element at the global scale, where an external force is applied (see Figure 1.



a) External applied forces, applied on whole element at global scale
b) Internal forces through material sections, due to applied force and material influences
c) Internal stresses in the materials, resultant internal forces over material cross-sectional area

Fig. 1. Modelling stresses in repaired concrete element using a global scale.

Using basic material mechanics and force compatibility, the internal forces at the cross-section of the repaired element can be decomposed into a substrate and repair component,

$$F_{\text{total}} = F_{\text{substrate}} + F_{\text{repair}} \,. \tag{1}$$

This additive decomposition enables the stresses in the substrate and repair to be determined for a given repair depth, as shown in Figure 1. As previously discussed, complete bond between the concrete substrate and repair material are assumed, implying strain compatibility. Thus, the following expression holds at any given point in time,

$$\varepsilon_{\text{substrate}}(t) = \varepsilon_{\text{repair}}(t) \,. \tag{2}$$

The shrinkage and creep strains in the substrate concrete are assumed to be negligible. Thus, the total strain in the substrate concrete is the elastic strain, resulting from the applied stress,

$$\varepsilon_s(t) = \sigma_s(t)/E_s \,. \tag{4}$$

The total strain in the repair material, however, is the sum of the strain due to the external loads, as well as shrinkage and creep in the repair material,

$$\varepsilon_r(t) = \sigma_r(t)/E_r + \varepsilon_{\text{creep}}(t) + \varepsilon_{\text{shrinkage}}(t) \tag{5}$$

The shrinkage strain experienced by the repair material ($\varepsilon_{\text{shrinkage}}$) was modelled based on the restrained shrinkage model by Beushausen [18], which is expressed here as:

$$\varepsilon_{\text{shrinkage}}(t) = \varepsilon_{\text{FSS}}(t) \cdot 1/(1+E_s/E_r), \tag{6}$$

The term ε_{FSS} is the free shrinkage strain of the repair material over time, the value of which was obtained from experimental testing (see Section 4.2).

The creep strain $\varepsilon_{\text{creep}}$ in equation (5) is more complex, though, as this component is dependent on the loads applied. Since the repair material undergoes creep and shrinkage over time, and that most of these strains in the substrate have already occurred, the stresses in the repair would also reduce over time. Most empirical research on creep were conducted using a constant stress. While some creep models do consider an incremental increase in load after a given amount of time, see Trost [19], there are currently no models that consider an incremental decrease in load. Another consideration is that only a certain percentage of creep is recoverable when loads are removed, with the remaining portion remaining irrecoverable. The developed expression for creep strain here thus considers the residual stress, an incremental decrease in load, and a portion that is irrecoverable, which is given as:

$$\varepsilon_{creep}(t_i) = C_{c,t_i}\sigma_{r,t_i} + \sum_{n=1}^{i} \rho_n C_{c,t_n}(\sigma_{r,t_{n-1}} - \sigma_{r,t_n}) + \sum_{n=1}^{i-1} X C_{c,t_n}(\sigma_{r,t_n} - \sigma_{r,t_{n+1}}) \tag{7}$$

The first term in equation (7) represents the creep strain due to the residual stress. The remaining two terms considers the irrecoverable creep strain between time steps *n-1* and *n*, after a decrease in stress, and the irrecoverable creep strain from the previous time steps *n* and *n+1,* after the stress has been relieved. The terms p_n is the aging coefficient that takes into consideration irrecoverable creep and X represents the percentage of irrecoverable creep strain over the time.

Equations (4) and (5) are substituted into (2) and solved simultaneously with (1) to determine the stress in the substrate concrete and repair material over time.

3 Repair material inputs

Three commercially available high strength cement-based repair materials were tested for their elastic modulus, shrinkage, and creep characteristics and used as inputs in the analytical model.

The materials consisted of a high strength (HS) grout, high strength (HS) concrete and ultra-high strength (UHS) grout. The mix proportions of each repair material are provided in Table 1 together with the corresponding compressive strength of each of the materials at different ages.

 https://doi.org/10.1051/matecconf/202236103002

Table 1. Repair material mix proportions.

	HS grout	HS concrete	UHS grout
Dry-mix content (kg/m^3)	2000	1645	2049
Water content (l/m^3)	280	230	246
9.5mm Greywacke (kg/m^3)	-	461	-
Water to dry-mix ratio	0.14	0.14	0.12
Tested compressive strength (MPa)			
- 1 day	39.4	41.7	36.3
- 7 day	59.3	66.8	61.7
- 28 day	70.7	77.0	79.3

3.1 Elastic modulus

The elastic modulus of each mix was determined by static elastic modulus in compression tests. Cylinders of 100 mm in diameter and 200 mm in height were tested at 1, 7 and 28 days of age. A load between 0.5 MPa and one third of their compressive strength was applied and displacement measurements taken on the circumferential face of the specimens using strain gauge extensometer. The results for the different mixes at the various ages are found in Figure 2 below. It is worth noting that the HS grout has a higher elastic modulus value at 28 days than the HS concrete containing coarse aggregates, which was not expected as the material containing aggregate was expected to have a higher elastic modulus than the one without. Furthermore, the 28-day elastic modulus of the HS concrete was lower than the same material tested at 7 days, the reason for which was unclear.

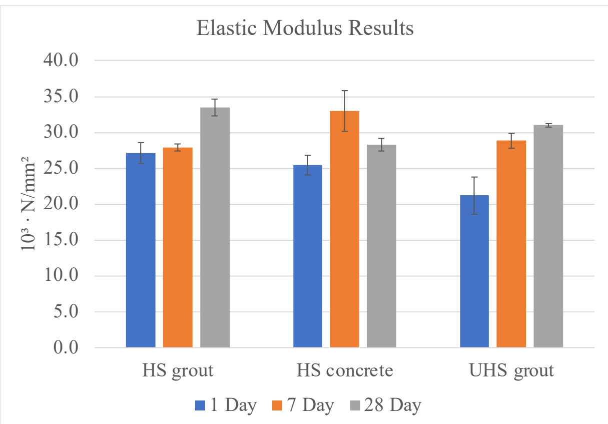


Fig. 2. Repair material elastic modulus results.

3.2 Shrinkage

The free shrinkage of each mix was determined using cylinders of 100 mm in diameter and 300 mm in height. Readings were taken 24 h after the samples were cast and intermittently over a period of 90 days. To record the strains, a strain gauge extensometer was used on targets attached to the sides of the cylinders. Figure 3 shows the shrinkage strains of the three mixes. The shrinkage strains for all three materials develop rapidly in the first 14 days, achieving between 84% and 90% of the total strain at 90 days. As shown, the shrinkage strain develops faster in the aggregate-bulked HS concrete than the HS and UHS grouts. This result was unexpected as research reports that the presence of coarse aggregate in repair materials reduces its total shrinkage strain [5,20]. A possible reason for this result could be attributed to the aggregate grading or moisture content, as poorly graded aggregates can create larger gaps in the pore structure allowing free movement of moisture out of the material.

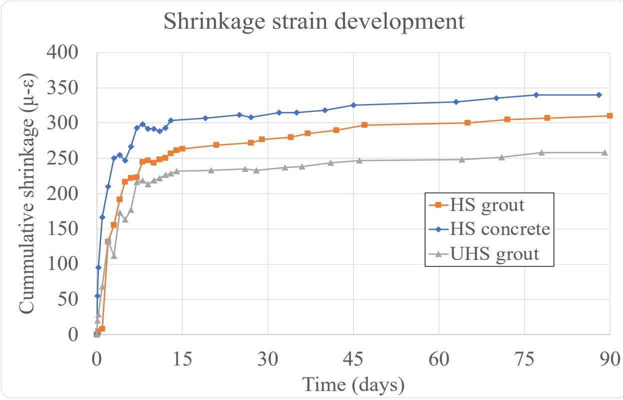


Fig. 3. Repair material shrinkage development results.

3.3 Compressive creep

The three repair materials were tested for their compressive creep characteristics. The specimens were loaded to stresses of 11.0 N/mm^2 and 19.8 N/mm^2 at 1 and 7 days of age, respectively. The applied stresses were equivalent to one third of the lowest compressive strength of the three materials, at the respective age of loading. The specific creep development results of the three repair materials, for the two loading ages, are shown in Figure 4 and 5, respectively.

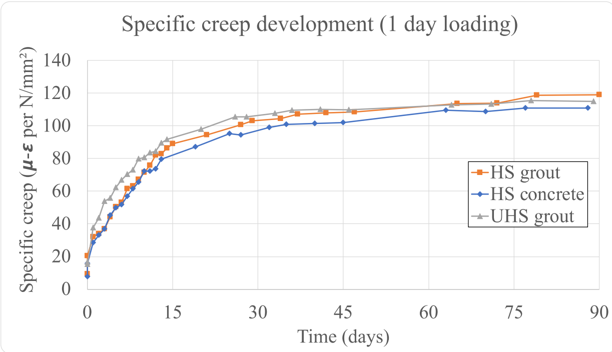


Fig. 4. Repair material specific creep development results (1 day loading).

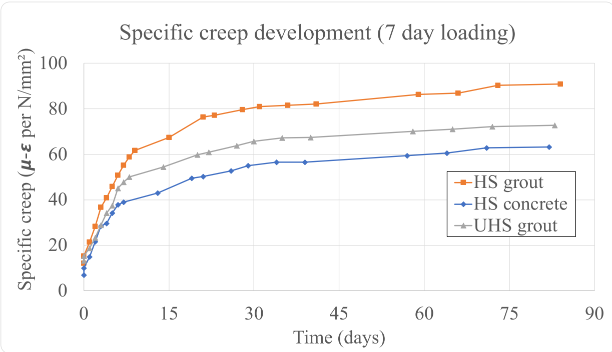


Fig. 5. Repair material specific creep development results (7 day loading).

For the materials loaded at 7 days of age, the specific creep development in all three materials became similar after 20 days of loading. However, at earlier ages the specific creep of the HS grout develops at a faster rate than both the HS concrete and UHS grout. The HS concrete had the slowest specific creep development of the three materials in the first 10 days of loading. This is similar to the results reported in past studies [5,20], where materials containing aggregate had lower creep strains than those without. Comparing Figures 4 and 5, the effects of aggregate were shown to be more pronounced at 7 days of loading than 1 day.

The specific creep development at different ages of loading (i.e. 1 day and 7 day) was compared for each material. The trends regarding the rate of specific creep development were similar for all three materials. The specific creep develops in each material at a similar rate after 30 days of loading, before which time the rate of development in specimens loaded at age of loading 1 day develop at a significantly faster rate than the specimens loaded at 7 day age of loading, i.e. the material specimens loaded at 1 day experience a noticeably higher magnitude of specific creep at each respective age of loading than those loaded at 7 days. These results are consistent with the studies by Yuan & Marosszeky [21] and Pan & Meng [22], where the creep strain properties were found to increase for a material loaded at earlier ages. Furthermore, Yuan & Marosszeky [21] found, concretes loaded at ages beyond 21 days were found to be less affected by these effects.

4 Model simulation results

4.1 Problem description

The repair scenario considers an unreinforced square column having a 500 × 500 mm cross-section that is subjected to an axial compressive load. The cross-sectional dimension of the repair is 100mm×500mm, representing 20% of the column's cross-sectional area.

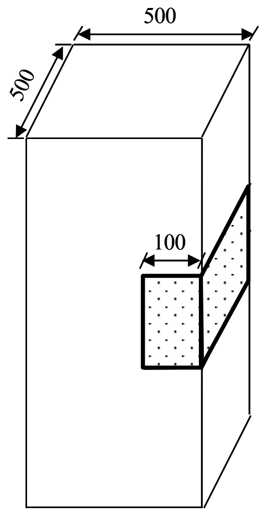


Fig. 6. Repair simulation geometry.

4.1.1 Material properties

The three high strength cementitious repair materials, discussed in Section 4, were used as the repair material inputs in the model. The substrate concrete material property inputs used in this example are found in Table 2.

Table 2. Substrate concrete material properties.

Material Property	Moderate-strength
Compressive Strength	40 MPa
Elastic Modulus	25 GPa

4.1.2 Load cases considered

A load stress of 25 MPa was applied to the repaired column. The repaired concrete element was loaded at 1 and 7 days after the repair, respectively. All loads were assumed to have been removed before the repair application and reapplied to the element after repair, at its respective age. The substrate concrete was assumed to undergo negligible creep strain recovery throughout the repair process.

4.2 Results

4.2.1 Distribution of stress in repaired element

Figure 7 shows the stress distribution between the substrate concrete and the HS concrete repair over the first 14 days of loading, which was applied 1 day after repair. As shown, the stress in the repair is similar to the concrete substrate but begins to rapidly decline in the first few days before flattening out, while the stress in the substrate concrete increases. This trend can be associated with the high rate of shrinkage and creep strain development in the repair material at early ages after loading, resulting in the transfer of stress from the repair material to the substrate concrete. After 14 days, the residual stress in the repair material was 2.7 MPa, representing 11% of the applied stress in the repaired element. This illustrates a low contribution by the repair material to the externally applied loads on the repaired concrete element.

After 69 days of loading, the stress in the HS concrete was less than 0.5 MPa, meaning the repair material is no longer contributing to the load carrying capacity of the concrete element.

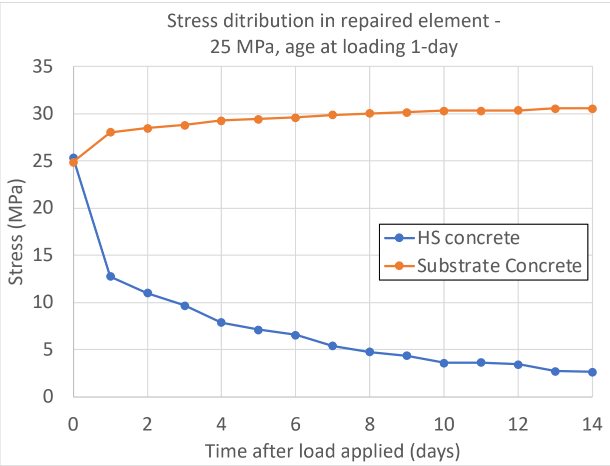


Fig. 7. Stress distribution in repaired element using HS concrete loaded at age of material 1 day.

5.2.1 Impact of different repair materials

The stress in the three repair materials over the first 14 days, loaded at 1 and 7 days after repair, is shown in Figures 8 and 9, respectively.

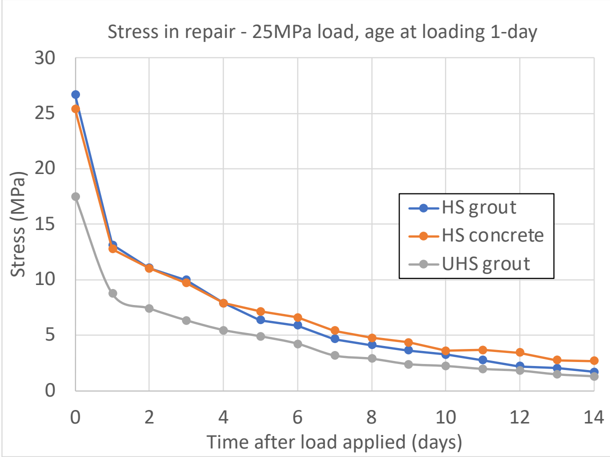


Fig. 8. Stress in repair material, age of loading 1-day.

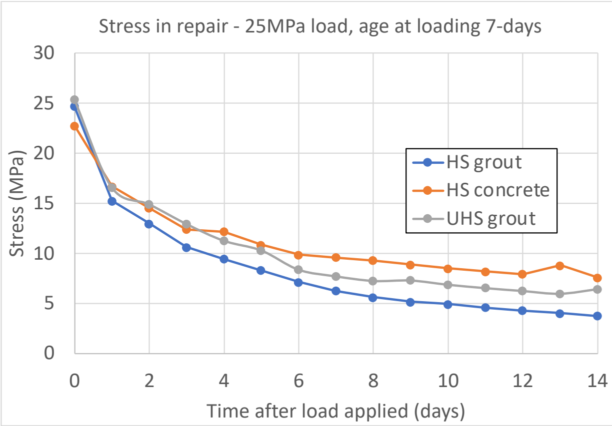


Fig. 9. Stress in repair material, age of loading 7-day.

For the columns loaded 1 day after repair, the decay of stress in all three repair materials follow a similar pattern. The stress in the UHS grout starts at a lower value, when compared to the HS grout and HS concrete, due to its comparatively low elastic modulus. The similar stress decay patterns are attributed to all three repair materials having similar shrinkage and creep characteristics. After 28 days, the model results show that the three repair materials only manage to retain 2-6% of the average stress in the repaired element. This represents a very low contribution by the repair materials to the external loads, when applied 1 day after repair.

The decay of stress in the three repair materials loaded 7 days after repair is more distinguishable over the 14 day period than those that were loaded 1 day after repair. The HS concrete manages to retain more of its stress over time, followed by the UHS grout and HS grout. Furthermore, the stress in the HS concrete and UHS grout experience increases slightly at days 13 and 14, respectively.

Within the first 28 days of loading, the repair materials were able to retain 10%-27% of the average stress in the repaired element, with the HS concrete performing the best of the three materials. However, after 95 days of loading, the stress in all three repair materials was below 0.5 MPa, again implying that the repairs are unable to structurally contribute in the long-term.

5 Conclusions

An analytical model was developed to approximate the stress behaviour in structural patch repairs of concrete elements under axial compression over time. The model considers material properties that have been shown to influence the stress distribution in repaired elements under axial compressive loads, specifically the elastic modulus, shrinkage and creep. Assumptions relating to bond at the interface of the repair and concrete substrate were made in developing the model, which is based on Hooke's law and Euler-Bernoulli beam theory and is limited to axial compressive stresses that act uniformly, with no load eccentricities. Time step increments of 1 day were used to approximate the elastic modulus and shrinkage and creep strains in the repair, the values of which were obtained from experimental testing, respectively. Using the results from experimental testing of high strength cement-based materials, a numerical example was presented to determine the efficacy of repair materials in structural patch repair applications. The ability of the repair material to contribute to load-sharing in the repaired element was the primary focus. The following conclusions can be drawn from this study:

- The stresses in the repair material, caused by loads reinstated after repair, are transferred to the substrate concrete over time due to the shrinkage and creep strains experienced by the repair material.

- The age of the repair materials at loading is inconsequential to the repair's ability to carry loads in the repaired member in the long-term, as there was effectively no remaining stress in the repair material beyond 90 days, irrespective of when the loads were applied.

- The high strength cement-based materials tested in this research were, effectively, unable to contribute to load sharing in the repaired element in the long-term. Such materials should thus not be considered as 'structural' repair mortars or grouts unless specific measures are taken to ensure their contribution in the long-term.

The research described in the paper was supported and funded by both the National Research Foundation of South Africa and, the Concrete Materials and Structural Integrity Research Unit at the University of Cape Town.

References

1. P. S. Mangat and F. J. O'Flaherty, Cem. Concr. Res. **30**, 125 (2000)
2. G. K. Glass, *Reinforcement Corrosion* (Woodhead Publishing Limited, 2003)
3. G. Tilly and J. Jacobs, CONREPNET Proj. Rep. (2007)
4. N. K. Emberson and G. C. Mays, Mag. Concr. Res. **42**, 161 (1990)
5. P. H. Emmons and A. M. Vaysburd, Constr. Build. Mater. **8**, 5 (1994)
6. D. Cusson and N. Mailvaganam, Concr. Int. Des. Constr. **18**, 34 (1996)
7. D. R. Morgan, Constr. Build. Mater. **10**, 57 (1996)
8. M. H. Decter and C. Keeley, Constr. Build. Mater. **11**, 267 (1997)
9. A. M. Vaysburd, B. Bissonnette, and K. F. von Fay, *Compatibility Issues in Design and Implementation of Concrete Repairs and Overlays* (2014)
10. C. Pellegrino, F. da Porto, and C. Modena, Constr. Build. Mater. **23**, 3129 (2009)
11. A. I. Ortega, T. M. Pellicer, P. A. Calderón, and J. M. Adam, Constr. Build. Mater. **186**, 338 (2018)
12. F. Da Porto, E. Stievanin, and C. Pellegrino, Cem. Concr. Compos. **34**, 545 (2012)
13. S. A. Kristiawan, A. Supriyadi, S. Sangadji, T. Anggraeni, and M. M. Pattiwael, Int. J. Adv. Struct. Eng. **11**, 31 (2019)
14. A. I. Ortega, T. M. Pellicer, P. A. Calderón, and J. M. Adam, Constr. Build. Mater. **177**, 1 (2018)
15. A. I. Ortega, T. M. Pellicer, P. A. Calderón, and J. M. Adam, Constr. Build. Mater. **161**, 53 (2018)
16. A. Sharif, M. K. Rahman, A. S. Al-Gahtani, and M. Hameeduddin, Cem. Concr. Compos. **28**, 734 (2006)
17. M. V. Shambira and G. Nounu, Constr. Build. Mater. **14**, 425 (2000)
18. H. Beushausen, Long-Term Performance of Bonded Concrete Overlays Subjected to Differential Shrinkage, University of Cape Town, 2005
19. Trost and H., Beton-Und Stahlbetonbau **10**, 230 (1967)
20. P. S. Mangat and M. K. Limbachiya, Constr. Build. Mater. **9**, 81 (1994)
21. Y.-S. Yuan and M. Marosszeky, Mater. Struct. **27**, 375 (1994)
22. Z. Pan and S. Meng, Eng. Struct. **120**, 23 (2016)