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CHARACTERISTICS OF STRAIN AGEING IN SD345 REINFORCEMENT AND ITS EFFECTS ON REPAIRED STRUCTURES

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ABSTRACT: Following observation of increase of strength of a 4-storey RC structure which was repaired and re-tested in a previous study, strain ageing of reinforcement was suspected to be the main reason. To verify the presence of strain ageing, tensile tests were conducted on grade SD345 D6 and D10 reinforcement. The results demonstrate that irrespective of the initial strain level, one year of strain ageing led to an increase in yield strength of 57 MPa (12%) and 81 MPa (19%) for D6 and D10 reinforcement, respectively. The ultimate stress also increased for both reinforcement types; however, at a smaller magnitude (2% and 6% increase for D6 and D10 reinforcement, respectively). Ultimate tensile strain was unaffected for D6 reinforcement but decreased by an average of 15% for D10 reinforcement. A simple strength calculation using results from the material testing confirmed that strain ageing was the principal cause for the increase in strength observed in the 4-storey structure.

Keywords: Repair, RC structure, Strain ageing, Strain hardening

1. INTRODUCTION

In efforts to minimize socio-economic disruptions following earthquake disasters, seismic design objectives are evolving to incorporate achieving rapid recovery and long-term infrastructure sustainability in addition to existing life-safety objectives. Part of achieving this goal is to minimize the demolition and reconstruction of damaged buildings and instead focus on repairing of the damage. In these efforts, verifying satisfactory performance of repaired structures in future earthquakes is of paramount importance. One concern regarding the performance of repaired structures that have experienced yielding in members is the potential of increase of hinge yielding strength due to 'strain ageing' of reinforcement (described in detail next). A higher than designed hinge strength can cause several adverse effects on the future performance of the structure, including a change in member failure mode from flexure to shear if the overstrength considerations are exceeded; change of collapse mode mechanism from beam-sway to column-sway (story-collapse mechanism) due to unaccounted overstrength of beams and reinforcement detailing concerns such as longitudinal reinforcement bond failure. Increase of structural strength after some initial damage has been previously observed in beam-columns joint tests [1] and in a 4-storey reinforced concrete (RC) frame-wall structure (hereon referred to as '4-storey structure') shown in Figure 1 [2,3]. In the latter study, a strength increase of 17% was measured following repairs of cracking, concrete spalling and reinforcement buckling damage. The repairs utilized common methods and generic like-for-like materials (epoxy resin, epoxy mortar and cementitious grout). Since no strengthening measures were implemented, the observed strength increase was partially attributed to strain ageing effects; however, these conclusions have not yet been verified through material testing. Though several past studies are available on strain ageing of New Zealand-manufactured reinforcement [4–7], the susceptibility of Japan-manufactured reinforcement to strain ageing effects is yet to be experimentally verified. The objective of this paper is in two parts: (i) to conduct tensile testing on the reinforcement used in the repaired 4-storey RC frame-wall structure [2] to ascertain through experimental testing if strain ageing did indeed occur and (ii) use the experimental data to demonstrate whether the 17% strength increase observed in the 4-storey structure could be explained by strain ageing.

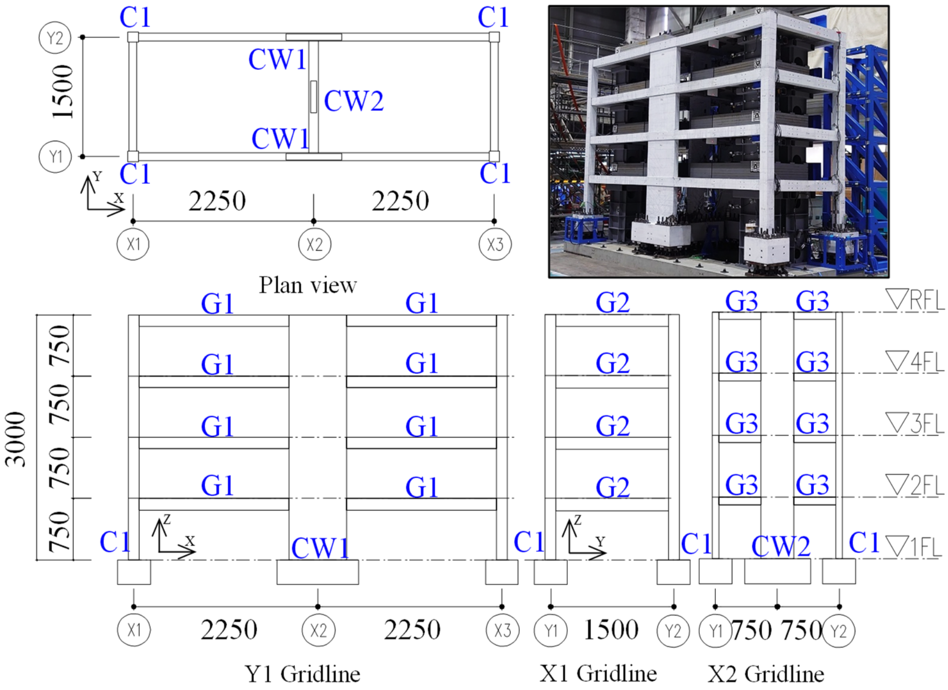


Figure 1: Dimensions of repaired structure (units: mm).

2. STRAIN AGEING OVERVIEW

As depicted in Figure 2, strain ageing is a phenomenon where yielding reinforcement once and storing in an unloaded state over an extended period of time results in the yield strength increase, $\Delta\sigma_{ya}$, beyond the strength that would be attained had the reinforcement been reloaded immediately (after accounting for strain hardening, $\Delta\sigma_{yh}$). Additional changes in the reinforcement properties include the reemergence of a yielding plateau, an increase in the ultimate tensile strength, $\Delta\sigma_{ua}$, and reduction in the fracture tensile strain, $\Delta\varepsilon_{ua}$ [6]. The strain ageing phenomena is thought to occur as a result of interstitial atoms (such as carbon or nitrogen) gradually migrating to and 'locking' dislocations in the atom crystal lattice that are created during reinforcement plastic deformation [8]. Thus, susceptibility of reinforcement to strain ageing effects is directly related to its chemical composition. Previous research has shown that addition of elements such as titanium and vanadium can suppress strain ageing effects by precipitating the interstitial nitrogen atoms into nitride compounds [4]. Previous testing on reinforcement steels used in New Zealand suggested that a yield strength increase of 10-20% can be expected depending on strain ageing period and the initial level of pre-strain [4–7].

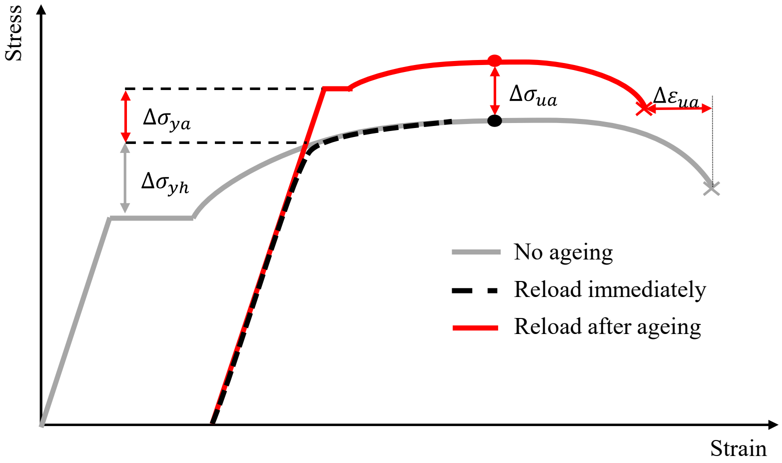


Figure 2: Definition of strain ageing and strain hardening in reinforcement.

3. EXPERIMENTAL PLAN

In this experimental program, longitudinal reinforcement used in the beams and walls of the 4-storey structure test were tested under uniaxial tension to verify the presence of strain ageing and the effect of the initial strain magnitude on the magnitude of strength increase. The longitudinal steel used in this experimental program was from the same batch used in the construction of the 4-storey structure. The D10 reinforcement was originally used for longitudinal reinforcement in the walls and columns, while the D6 reinforcement was used for longitudinal reinforcement in the beams. Details of the reinforcement grades and their chemical compositions are listed in Table 1. It can be seen that neither of the two reinforcement types tested contained vanadium, an element known to suppress strain ageing effects [4].

Table 1 Chemical composition of D6 and D10 reinforcement*.

Diameter	Grade	Yield strength* [MPa]	Chemical composition (x1000)					
			C	Si	Mn	P	S	V
D6	SD345	398	260	280	1090	19	12	0
D10	SD345	370	210	200	970	27	22	0

*Mill sheet data.

The test procedure was to first subject each reinforcement type to an initial tensile strain ranging from 1-6%; releasing the load; inducing strain ageing and retesting each reinforcement until fracture. The test matrix is shown in Table 2. The yield strength, σ_y, ultimate strength, σ_u and strain at fracture, ε_u, were measured. The strain at fracture was determined by measuring the change in the distance between two punch marks made on the reinforcement prior to testing. The punch marks were approximately 25 mm apart and in every reinforcement piece were either side of the eventual fracture point. Three reinforcement pieces were tested for each initial strain parameter. The results reported in this paper correspond to the average of the three test pieces. Additionally, as a base for comparison a ‘control’ reinforcement piece was tested to fracture without subjecting to strain ageing effects. To simulate a one year period of strain ageing (the delay between the testing of original and repaired 4-storey structure), a heat treatment process of reinforcement was used. In the heat treatment process the reinforcement was placed into an pre-heated oven and held at a constant temperature of 100 °C for a period of 4 hours (previous research suggests this is roughly equivalent to one year strain ageing at 15 °C [9]). After removing from the oven, the reinforcement test pieces were allowed to naturally cool to room temperature (22 °C).

Table 2 Test matrix of experimental program.

Diameter	Initial strain					
D6	0%	1%	2%	3%	4%	6%
D10	0%	1%	2%	3%	4%	6%

4. TEST RESULTS

Final test results for each initial strain value (averaged over the three test pieces) are summarized in Table 3 and Table 4 for D6 and D10 reinforcement, respectively. As shown in Figure 2, the difference between the peak stress and yield stress recorded during initial loading is taken as the strength increase due to strain hardening, $\Delta\sigma_{yh}$. The increase in strength due to strain ageing, $\Delta\sigma_{ya}$, was calculated as the difference between the peak stress recorded during the application of initial strain and the yield stress recorded after strain ageing, σ_{ya}.

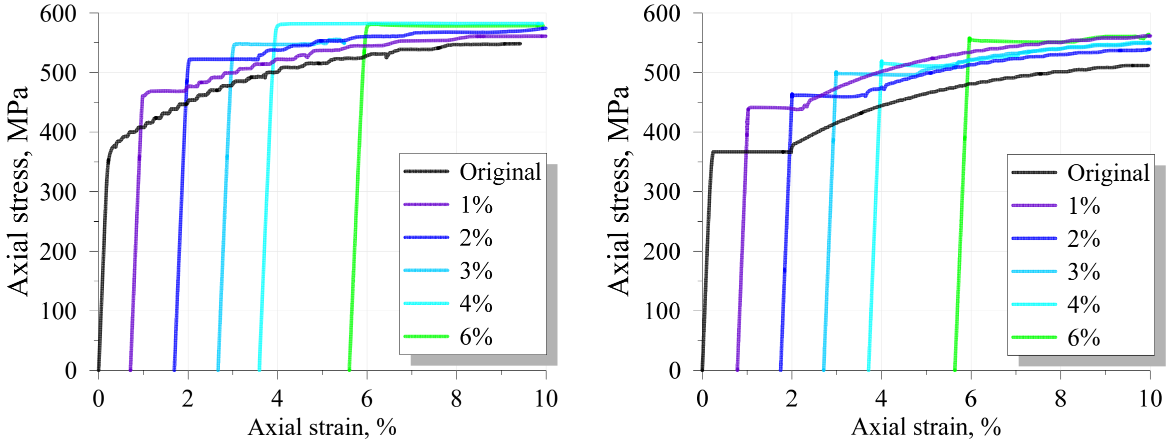
Representative stress-strain curves for each initial strain level are shown in Figure 3a and 3b for D6 and D10, respectively. The stress-strain curve of the control test piece is indicated as a black line in each figure. It can be observed from the results that D6 and D10 reinforcement exhibit an increase in yield strength and re-emergence of a yield plateau; thus, confirming the susceptibility of this reinforcement to strain ageing. In the case of D6 reinforcement, the yield plateau is not present for the control test piece, suggesting that some cold work has occurred. This was likely the result of straightening the D6 reinforcement from their usual coil storing configuration. In both the D6 and D10 reinforcement, the post-strain ageing curve exceeds the envelope of the control reinforcement backbone curve. The changes in yield stress, ultimate stress and strain at fracture will be discussed in detail next.

Table 3 Strain ageing test results for D6 reinforcement.

Initial strain [%]	σ_y [MPa]	E [GPa]	σ_u [MPa]	σ_{ya} [MPa]	ε_u	$\Delta\sigma_{yh}$ [MPa]	$\Delta\sigma_{ya}$ [MPa]
0	**403**	**184**	**569**		**0.26**		
1%	388	183	574	479	0.28	37	54
2%	389	182	581	532	0.29	79	62
3%	384	182	580	552	0.25	110	57
4%	392	185	587	583	0.28	132	56
6%	383	186	585	585	0.27	147	55
Avg.	390	184	579	546	0.27	101	57

Table 4 Strain ageing test results for D10 reinforcement.

Initial strain [%]	σ_y [MPa]	E [GPa]	σ_u [MPa]	σ_{ya} [MPa]	ε_u	$\Delta\sigma_{yh}$ [MPa]	$\Delta\sigma_{ya}$ [MPa]
0	**360**	**182**	**536**		**0.43**		
1%	359	187	570	432	0.38	0	73
2%	356	183	570	462	0.38	27	89
3%	361	184	548	510	0.38	66	83
4%	361	185	562	520	0.33	91	80
6%	366	186	571	560	0.38	116	78
Avg.	361	185	559	497	0.38	060	81



(a) D6 (b) D10

Figure 3: Stress-strain relationship for reinforcement pre- and post-strain ageing.

4.1 Yield stress

The increase in yield stress as a result of strain ageing, $\Delta\sigma_{ya}$, are plotted in Figure 4a. The results in this figure suggest that for both D6 and D10 reinforcement the increase in strength due to strain ageing is independent of the magnitude of initial strain. The horizontal dotted lines in the figure represent an average stress increase taken across all the initial strain scenarios. The average increase from the peak stress achieved during initial strain loading is 57 MPa (12% increase) and 81 MPa (19% increase) for D6 and D10 reinforcement, respectively. The stress increase in D6 reinforcement is lower than D10 reinforcement, and this is partially attributed to the fact that D6 reinforcement had undergone some initial level of strain hardening during straightening.

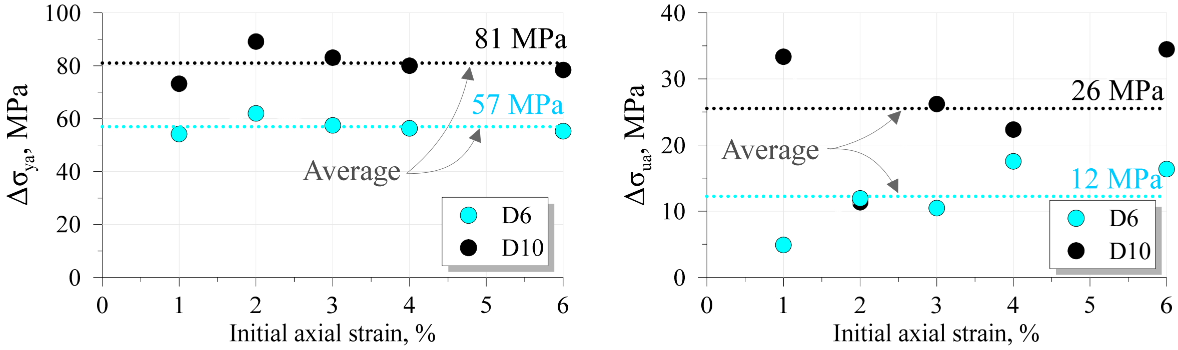
4.2 Ultimate stress

The change in ultimate stress due to strain ageing effects, $\Delta\sigma_{ua}$, is shown in Figure 4b as a function of initial strain. For D6 reinforcement the ultimate stress after strain ageing is observed to increase as the level of initial strain increases. However, this increase is only in the range of 5-17 MPa (average of 12

MPa; 2% higher than the control test piece). The D10 reinforcement also exhibited an increase in ultimate stress following strain ageing; however, the appears to be no clear dependency of the increase magnitude on the level of initial strain. With the exception of the 2% pre-strain case, the ultimate stress increase in D10 reinforcement is higher than that observed in D6 reinforcement. The average ultimate stress increase of D10 reinforcement is 26 MPa (6% higher than the control test piece).

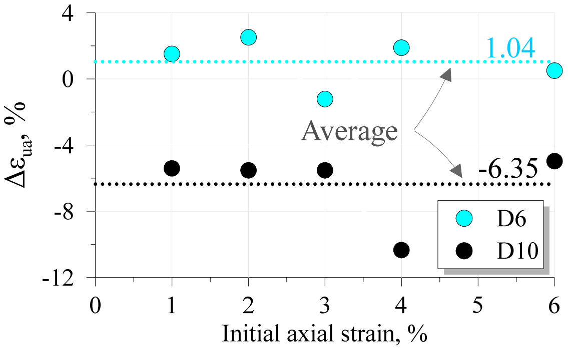
4.3 Strain at fracture

The change in percentage strain at fracture as a function of initial strain is plotted in Figure 4c. For D6 reinforcement it can be seen that the strain ageing has no apparent influence on the change in strain at fracture (on average +1% strain change), irrespective of level of initial strain. For D10 reinforcement an average reduction of 6.35% strain at fracture is observed due to strain ageing; however, this reduction (15% of the control reinforcement) appears to not be dependent on the level of initial strain.



(a) Change in yield stress

(b) Change in ultimate stress



(c) Change in ultimate tensile strain

Figure 4: Change in stress and strain properties of reinforcement post-strain ageing.

5. ESTIMATE OF STRENGTH INCREASE IN THE 4-STOREY STRUCTURE

As mentioned in the introduction, a strength increase of 17% was measured in a 4-storey structure following simple repair of structural damage. In this section, the results of the material study presented above are used to evaluate whether the 17% increase could be adequately explained by strain ageing effects. To achieve this, a comparison is made between the sum of the moment capacities of all flexural hinges in the 4-storey structure before and after repair (i.e., 4 column hinges, 32 beam hinges and 2 wall hinges). The individual hinge strengths, M_u, were calculated using the Architectural Institute of Japan standard [10] (with exception of walls, where moment capacity was calculated from section analysis as the point at which the extreme concrete compression fiber reached a strain 0.003). For calculation of hinge strengths after repair (i.e., accounting for strain ageing), the yield stress of longitudinal reinforcement in each hinge was increased from the original strengths in Table 1 by the average values indicated in Figure 4a. The total moment capacity results for the 4-storey structure before and after repair are listed in Table 5. From this rough calculation a 13.7% overall increase in structural strength is estimated for the 4-storey structure after repairs, which is in reasonable agreement with the experimentally determined 17%. The results of this study suggest that strain ageing was indeed the principal cause of the observed 17% increase in strength following repairs of the 4-storey structure. The 3.3% discrepancy with the estimated strength increase can likely be attributed to additional reinforcement strain hardening that occurred during testing of the structure following repairs. As a strength increase of this magnitude can lead to potentially unexpected failure modes, it follows that strain ageing should be an important consideration in the repair decisions of damaged structures.

Table 5: Estimate increase in total structural capacity due to strain ageing.

	Before repair		After repair	
	M_u kNm	Total kNm	M_u, kNm	Total kNm
Column	7.0	28.0	8.0	32.0
Beam (+ve)	4.4	70.4	4.9	78.4
Beam (-ve)	10.0	160.0	10.5	168.0
Wall	246.0	492.0	287.4	574.8
Total capacity		**750.4**		**853.2**

1) +ve refers to positive bending, i.e., top fiber in compression, and -ve refers to negative bending, i.e., top fiber in tension.

6.CONCLUSIONS

Following observation of increased strength of a 4-storey RC test structure following simple repairs in a previous study, strain ageing of reinforcement was suspected to be the main reason. An experimental study was conducted on reinforcement equivalent to that used in the 4-storey structure to determine if the observed strength increase could be adequately explained by the strain ageing phenomena. From the material study the following conclusions can be made:

1) Both the D6 and D10 (Grade SD345) reinforcement exhibited strain ageing susceptibility characteristics. Yield strength was found to increase on average by 57 MPa (12%) and 81 MPa (19%) for D6 and D10 reinforcement, respectively, relative to the peak stress upon initial loading. The increase in yield strength was not dependent on the level of initial strain for either reinforcement type.
2) The increase of ultimate stress of the reinforcement as a result of strain ageing was not as significant as the increase in yield strength. The increase was found to be on average 2% and 6% higher than the control D6 and D10 reinforcement, respectively.
3) The ultimate tensile strain was found to be unaffected by strain ageing for D6 reinforcement. For D10 reinforcement, an average reduction of 15% was observed over all initial strain levels compared to the control test pieces.
4) Comparison of sum of all hinge flexural strengths before and after strain ageing of the 4-storey structure suggested that the most of the observed strength increase (13.7% of 17%) could be explained by strain ageing effects.

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