Fiber Reinforced Mortar for the Repair of Concrete Slab with Significant Loss of Steel Area due to Corrosion

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Presentation at SCCT Annual Concrete Seminar, 2nd April, 2019

Outline

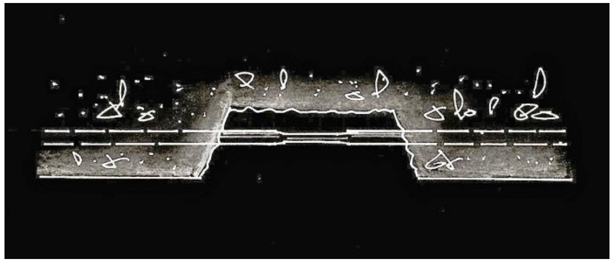
- Background
- Development of Fiber Reinforced Repair Material
- Concept Verification
  - Testing of ‘Corroded’ Rebar with Repair Mortar
  - Testing of Repaired Slab with ‘Corroded’ Rebar
- Testing to Address Practical Concerns
  - Fire Test
  - Effect of Steel Fiber on Rebar Corrosion
- Conclusions and Further Work

Background

- Buildings in Hong Kong are aging and degrading
- Mandatory Building Inspection Scheme (MBIS) requires buildings over 30 years old to be inspected
- According to experience from Housing Department, Building close to 40 years old are having a lot of problems with steel corrosion and the associated concrete spalling
- There are currently around 40,000 public rental housing units over 40 years of age and the number will be tripled in a few years time
- Localized corrosion and spalling are commonly found

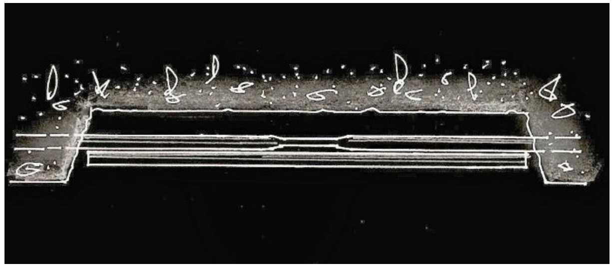
Conventional Repair Method

(1)



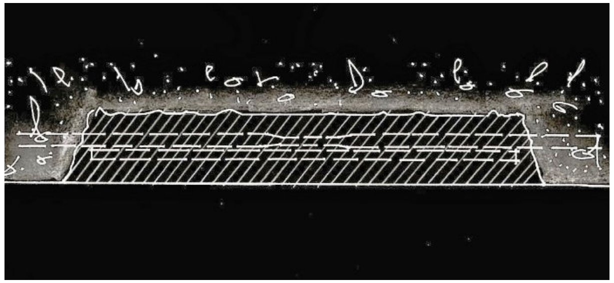
- Expose area of corroded rebars in concrete slab;
- Make good corroded rebars

(2)



- Extend the area of concrete removal to expose good rebars for lapping;
- Fix replacement rebars

(3)



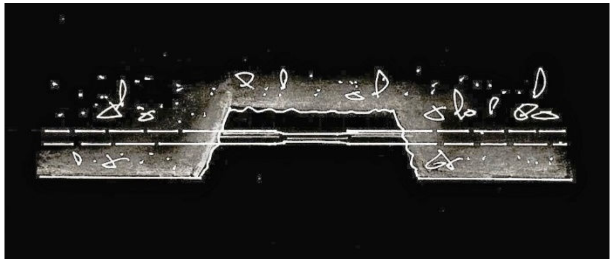
- Conduct inspection of rebar lapping;
- Carry out patching using conventional repair mortar;
- Inspect completed repair works

- ✘ *Significant additional concrete area exposed for lapping of rebar*
- ✘ *Labour intensive and time consuming*
- ✘ *More Noise and Dust produced*

Proposed New Approach

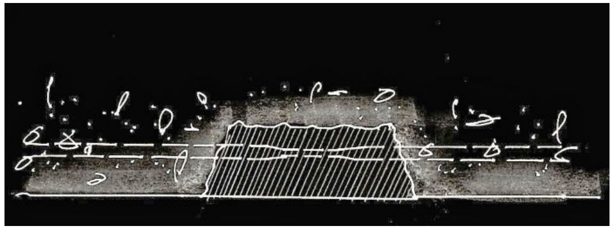
- ❑ Add fibers into the repair mortar so it can carry tensile stress
- ❑ For moderate steel area loss, lapping of new rebar is no longer necessary

(1)



- Expose area of corroded rebars in concrete slab;
- Make good corroded rebars

(2)

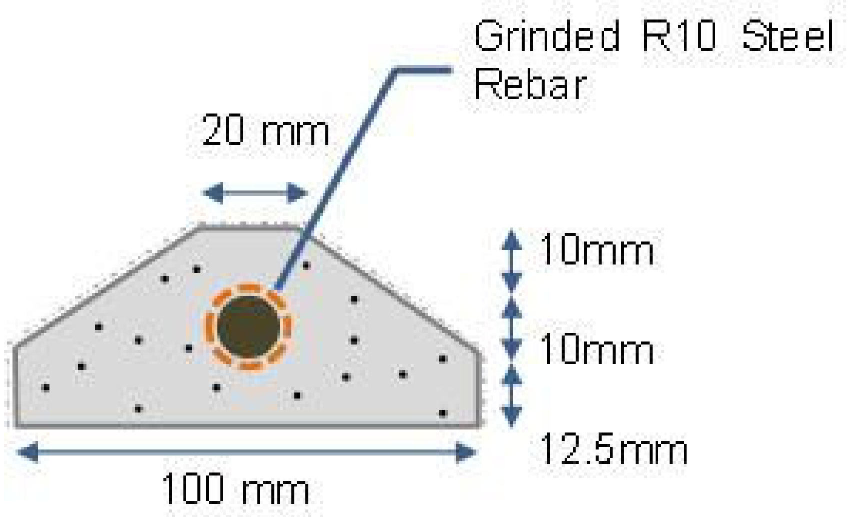


- Carry out patching using fiber reinforced repair mortar;
- Inspect completed repair works

✓ *Exposed concrete area for lapping greatly reduced*
✓ *Simplified repair process with savings in labor and cost*
✓ *Shorter time to commence repairing with less dust and noise*

Simple Calculation to Illustrate Feasibility

- Focus on repair of concrete slabs in old buildings with 10mm mild steel rebar losing up to 40% of cross sectional area



Typical Geometry of Repair Mortar Patch with 'Conservative' Dimensions (according to Housing Department)

Cross-sectional Area of Repair Mortar Patch
$= 2371\text{mm}^2$

Tensile stress to compensate 40% loss in steel area
= 40% rebar area x rebar strength /mortar area
$= (40\% \times \pi \times 10\text{mm}^2 / 4) \times 250\text{MPa} / 2371\text{mm}^2$
$= 3.31\text{MPa}$

Hence, a fiber reinforced mortar with **tensile strength of 3.5MPa or above** will suffice

From experience, this is achievable with the use of steel fibers. To prevent rusting, stainless steel fibers will be used.

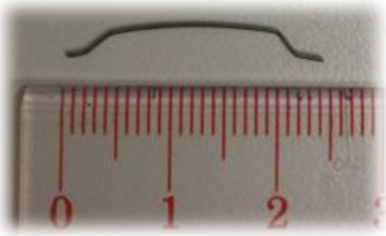
Materials for the Repair Mortar

<u>Mortar</u>

- ❑ 5 Commercial Mortars with incorporation of fibers were studied
- ❑ A new mortar developed by Chunwo-NAMI was also considered

<u>Fiber</u>

- ❑ 3 types of stainless steel hooked-end fibers were tested
  - (a) 0.4mm x 25mm
  - (b) 0.75mm x 50mm
  - (c) 0.65mm x 60mm



0.4mm × 25mm
Aspect ratio = 62.5

0.75mm × 50mm
Aspect ratio = 66.7

0.65mm × 60mm
Aspect ratio = 92.3

Tests to Develop the Fiber Reinforced Mortar

- Standard tests to fulfil basic requirements of repair mortar
  Compressive strength, tensile strength, elastic modulus, bond strength, Shrinkage (Ring test), air permeability
  - All tested mortar fulfill the above tests
- Direct tensile test on the fiber reinforced mortar
  - Specimens prepared with different kinds of mortar containing various volume fractions of fiber
  - Target strength: 3.5MPa
- Instant thickness test
  - To test the ability of the mortar to stay on downward facing surface without dripping
- Bond tests on mortars selected based on the above tests
  - To find the bond length along the rebar for transferring loading to the part with reduced steel area

Direct Tensile Test – Specimen Preparation

Add dry mortar into the container

Mix mortar with mixing machine for 5mins and add water gradually during the mixing

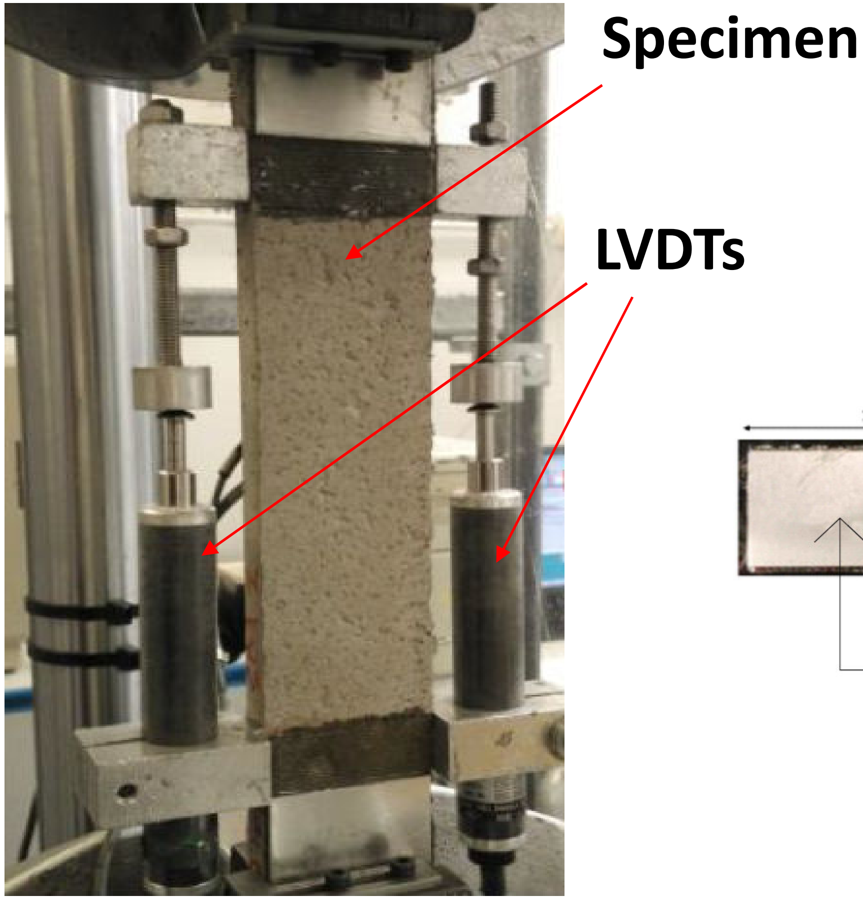
- Squeeze fiber mortar into strips
- Strips placed in such a way to enhance fiber alignment along loading direction

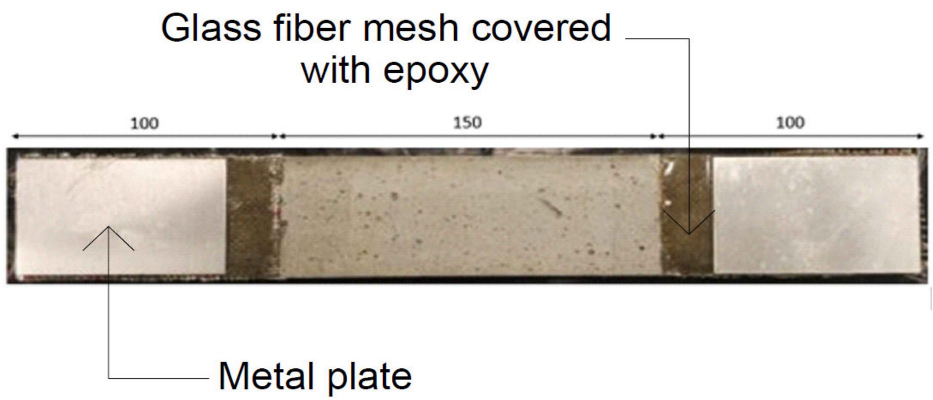
Disperse short fibers into dry mortar

OR

Add long fibers into the mixture and mix it by hands

Direct Tensile Test – Testing Setup

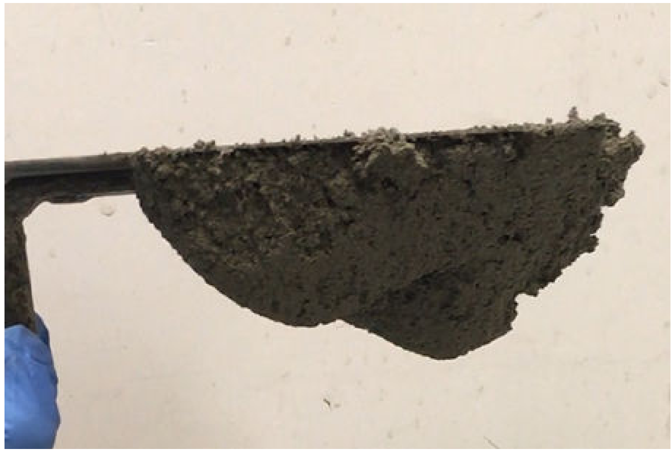




Strengthening of Specimen at its ends to prevent local failure

Instant Thickness Test

- Fresh mortar was taken from the mixer with a trowel and then turned to face downward
- The maximum height it can sustain without dropping is measured as the instant thickness
- This property is helpful to ensure ease of application as well as good bonding between mortar and substrate (as tendency to drop may lead to formation of gaps)



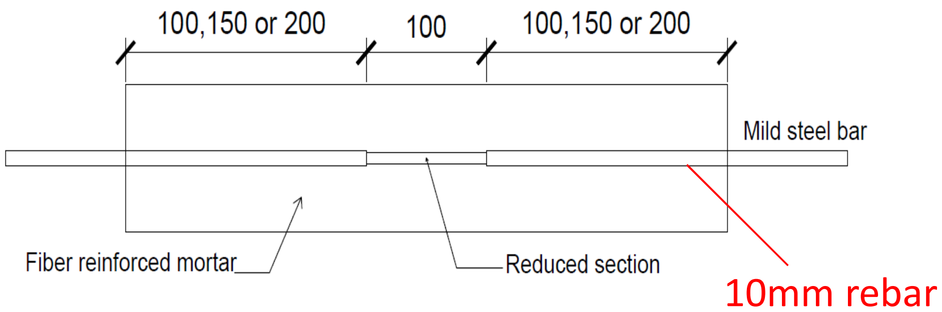
Instant thickness

Summary of Results from the Above Tests

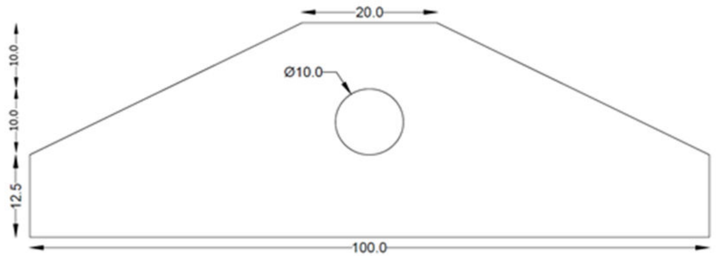
- The target strength of 3.5MPa can be achieved for several kinds of mortar by adding 2% of fiber with aspect ratio of 92.3 (60mm length and 0.65mm diameter)
- Based on the direct tensile test and instant thickness test, the following mortars (with fiber) were considered suitable for further tests
  - Mapei
  - Ronacrete
  - Chunwo-NAMI
- Other mortars should NOT be considered inferior
  - they may perform well with other kinds of fibers
  - None of the mortars are designed for use with fibers. If there is a market, compositions can be modified

Bond Test

- ❑ Loading need to be transferred from the full steel section to the section with reduced area due to corrosion
  - ➢ The required bond length is an important design parameter
- ❑ Testing performed on a specimen with reduced steel rebar area in the middle
- ❑ Section of the specimen follows the geometry of a typical patch
- ❑ Specimens prepared with three selected mortars

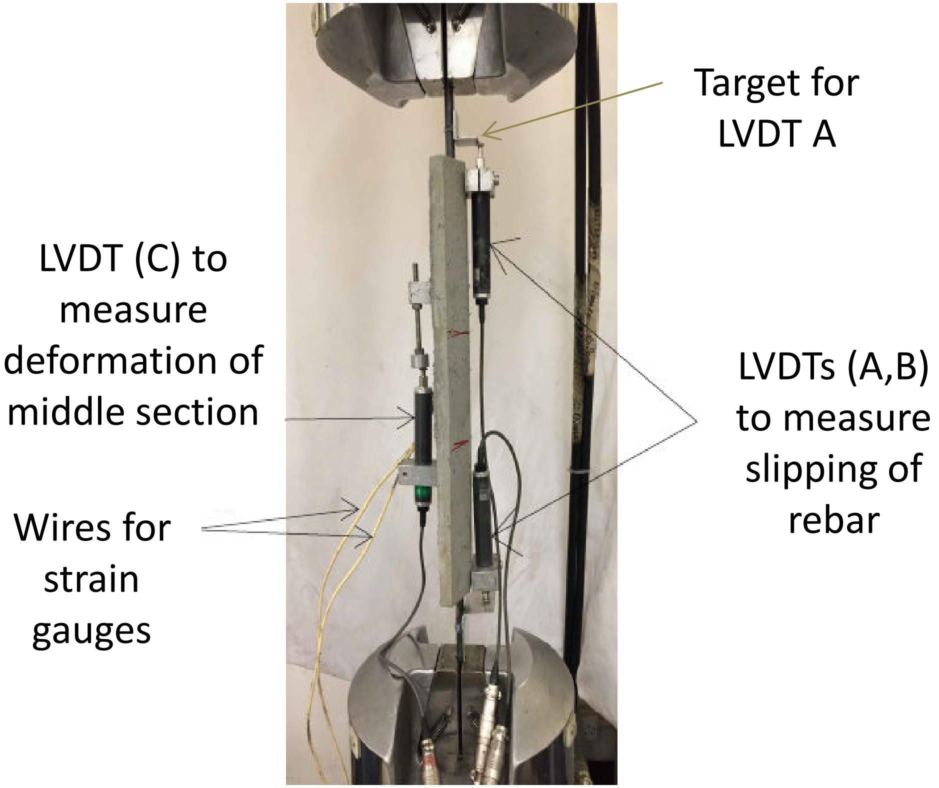


Bond Test Specimen

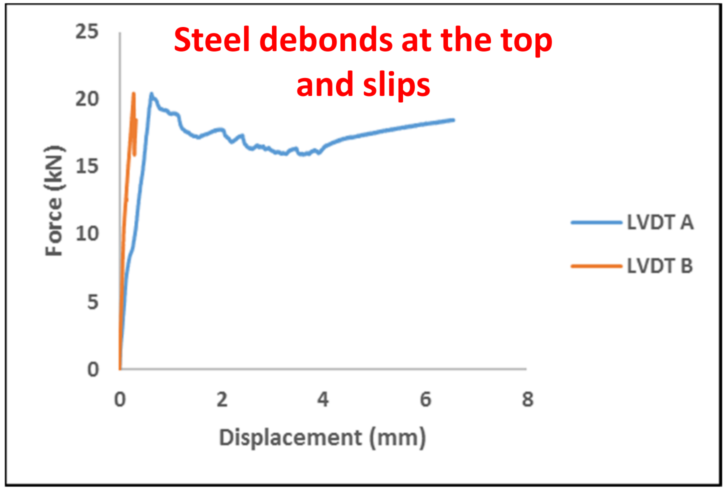


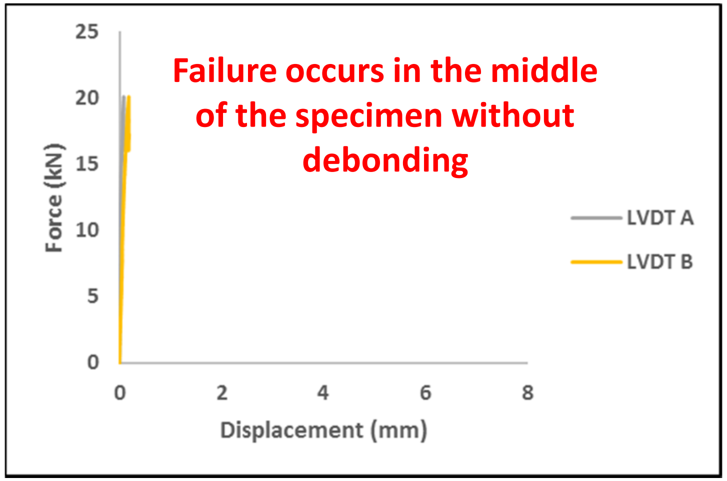
Section of the Specimen

Bond Test Set-up and Typical Results



Set-up for the Bond Test





Percentage Recovery of Load Carrying Capacity

- Mild steel with 250MPa yield strength used in old buildings, but testing is performed with 320MPa rebars
- Need to find out if the load capacity of corroded rebar with 250MPa strength can be recovered

$$P - \sigma_{320} \times A_s' = F$$

Measured Load Capacity (P); Steel strength (σ_{320}); Reduced steel area (A_s'); Contribution from Repair Mortar (F)

$$F + \sigma_{250} \times A_s' = Q$$

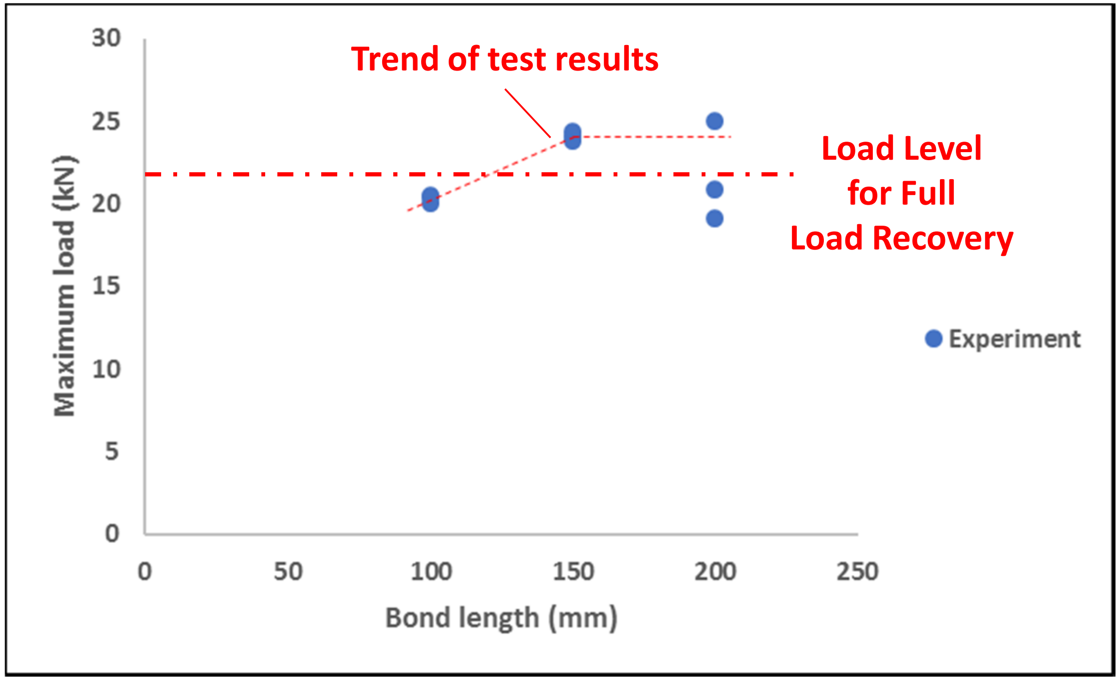
Load capacity if Rebar strength is 250MPa (Q)

$$\text{Percentage of recovery} = \frac{Q}{\sigma_{250} \times A_s} \times 100\%$$

Full steel area (A_s)

Summary of Test Results

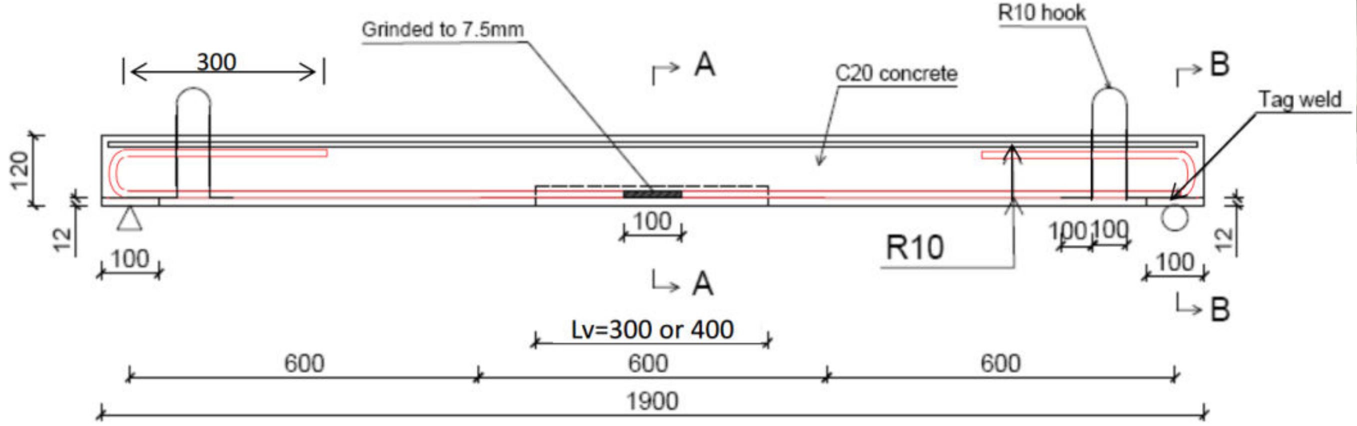
<u>Results for one repair mortar</u>

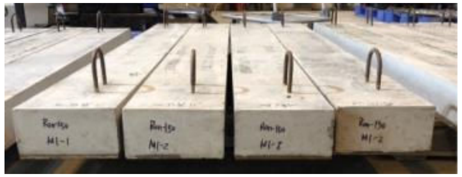


- ❑ 150mm bond length is sufficient to recover full strength of 250MPa rebar
- ❑ With 100mm bond length, over 90% of the load capacity can be recovered
- ❑ Further studies on slabs will be performed with 100mm and 150mm bond length

Specimens for Four-Point Bending Test

- Specimens with single 10mm rebar (middle grinded to 7.5mm) were prepared
- The two ends of the embedded rebar were hooked to avoid bond slip
- The <u>Length of trapezoid void, Lv, were set as 300mm and 400mm</u> to further investigate effect of bond lengths (which are 100mm and 150mm respectively) between repair mortar and steel rebar





Specimens Fabricated and Patching Plan

	Beam Type	Bond Length	Mortar for Patch-up[Note 1]	No. of Beams
	Control A (Full Rebar)	---	---	2
	Control B (Rebar with 40% loss)	---	---	2
Four-point bending test	Lv = 400	150 mm	Ronacrete	2
			Mapei	2
			Chunwo-NAMI RM	2
	Lv = 300	100 mm	Ronacrete	2
			Mapei	2
			Chunwo-NAMI RM	2

Note 1:

- *Bond coat was applied on parent concrete substrate before applying Ronacrete and Mapei*
- *no bond coat was applied for Chunwo-NAMI's RM.*

Beam Patching

1) Roughen concrete substrate by vibrating needle gun



2) Prepare mortar composite according to the developed mixing procedure



Beam Patching (continued)

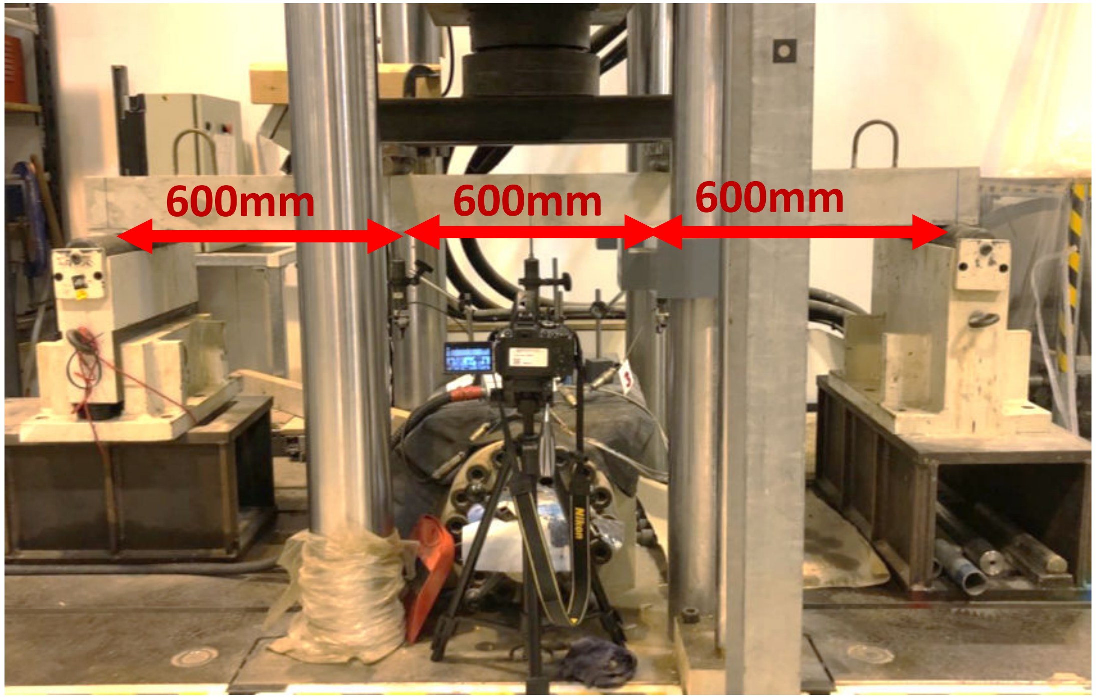
3) Prepare mortar composite according to a standard mixing procedure

4) Final patched beams

Test Setup for Four-Point Bending Test

- The beams span was 1.9 m. Two point loads were applied at one-third and two-third of beam span.
- The beam specimens were conducted with displacement control mode at the rate of 0.01mm/sec.

Test Setup



RC Beam Subjected to Four Point Bending

Percentage of Recovery – Calculation Method

- ❑ Mild steel with 250MPa yield strength used in old buildings, but testing is performed with 320MPa rebars
- ❑ Need a way to calculate the load carrying capacity of the fibers and then assess if they are sufficient to fully recover the strength of slab with corroded 250MPa rebar

Method 1

From control beam with full steel rebar

$$\begin{cases} M_p = f_c bx\left(h_0 - \frac{x}{2}\right) \\ f_p A_s = f_c bx \end{cases} \Rightarrow f_p \Rightarrow M_f = M_p - M_{p,f_p,60\%} \Rightarrow \text{\% of recovery} = \frac{M_f + M_{p,250,60\%}}{M_{p,250,100\%}}$$

Moment capacity contributed by steel fibers

Based on steel rebar strength *fp* calculated from the control beam

Method 2

$$M_f = M_p - M_{p,\text{control},60\%} \Rightarrow \text{\% of recovery} = \frac{M_f + M_{p,250,60\%}}{M_{p,250,100\%}}$$

Measured from the control beams with reduced steel area

Percentage of Recovery - Results

	F_{cr} (KN)	F_p (KN)	M_p (KNm)	% of Recovery (by Method 1)	% of Recovery (by Method 2)
Ronacrete-150-1	4.6	11.33	3.4	117.3	108.2
Ronacrete-150-2	4.11	10.53	3.159	105.1	96.0
Mapei-150-1	4.76	11.27	3.381	116.3	107.2
Mapei-150-2	3.91	10.96	3.288	111.6	102.5
Chunwo-NAMI-150-1	3.66	10.37	3.111	102.7	93.6
Chunwo-NAMI-150-2	3.61	11.84	3.552	125	115.9
Ronacrete-100-1	4.53	9.74	2.922	93.2	84.0
Ronacrete-100-2	4.44	9.21	2.763	85.1	76.0
Mapei-100-1	5.08	9.84	2.952	94.7	85.6
Mapei-100-2	4.97	10.45	3.135	103.9	94.8
Chunwo-NAMI-100-1	3.89	9.63	2.889	91.5	82.4

Full recovery is achievable with all three repair mortars for bond length of 150mm

- 150mm bond length is hence recommended for practice

Additional Tests with Chunwo-NAMI Mortar

- Chunwo-NAMI mortar with modified compositions were used
- Effect of Bond Coat was also studied
- Capacity well above original uncorroded member with or without bonding agent
- Full recovery consistently achieved even with 100mm bond length

	F_{cr} (KN)	F_p (KN)	M_p (KNm)	% of Recovery (by Method 1)	% of Recovery (by Method 2)
With Bond Coat					
Chunwo-NAMI-100-1	4.46	13.19	3.957	145.1	136.4
Chunwo-NAMI-100-2	4.54	13.05	3.915	143.0	134.2
Chunwo-NAMI-150-1	4.08	13.72	4.116	153.1	144.4
Chunwo-NAMI-150-2	4.18	13.6	4.08	151.3	142.6
Without Bond Coat					
Chunwo-NAMI-100-1	3.73	11.85	3.555	124.8	116.0
Chunwo-NAMI-100-2	3.14	12.63	3.789	136.6	127.9
Chunwo-NAMI-150-1	3.96	13.66	4.098	152.2	143.5
Chunwo-NAMI-150-2	4.00	14.28	4.284	161.6	152.9

Cyclic Bending Test

- Additional beams have been prepared for cyclic bending test
- Very extreme condition with 10 cycles of full live load per day over 30 years, giving a total of 110,000 cycles
- After the test, the beam specimens remained intact. No visual crack or debonding was observed.
- Flexural strength was similar to those directly loaded to failure.

Side Face (No crack observed)

Bottom Face (No debonding found at the concrete/mortar interface)

Full-scale Fire Test of Repaired Concrete Slabs

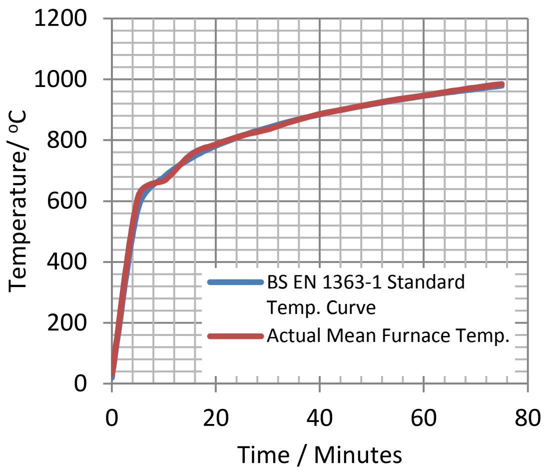
- ❑ Four specimens prepared for fire testing, one control and three with one of the steel rebars exhibiting 40% area reduction, repaired using fiber reinforced mortar
- ❑ For the repair, the bond length on each side was 150mm
- ❑ Following code requirements, specimens were loaded with dead weight equivalent to 5kPa during fire exposure

Ronacrete Unicell 25 | NAMI-RM | Mapei HB25

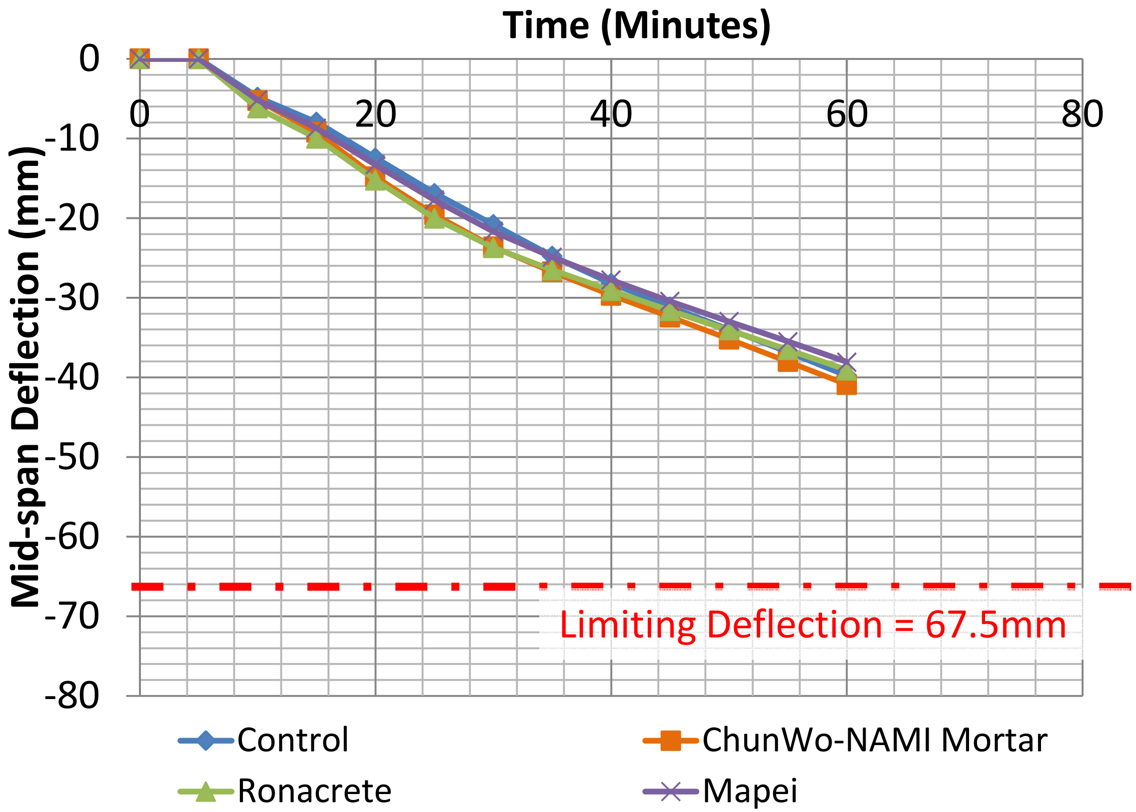
Specimens before Fire Testing

Fire Testing Set-up

Full-scale Fire Test of Repaired Concrete Slabs



Temperature vs time curve according to BS EN 1363-1



- ❑ The deflection of all four specimens was within the deflection limit and deflection rate limit specified in the fire test standard.

Slab specimens after fire test

No cracking or separation identified in the repaired patch

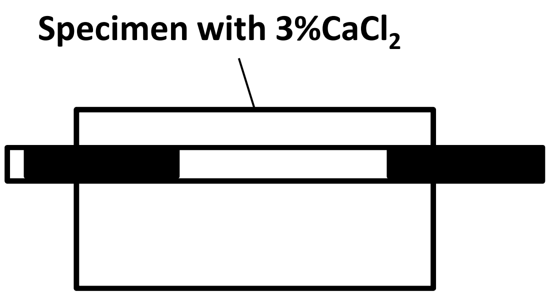
Corrosion Behavior of Steel Rebar Surrounded by R2M2 (1/2)

<u>Concerns</u>

- Would steel fibers increase conductivity and so accelerate steel corrosion?
- Would stainless steel fibers form galvanic cell with steel rebar?

<u>Test 1</u>

- Self-corrosion in repair mortar with and without fibers
- Both half cell potential and corrosion current are measured
- The specimens with steel fibers show lower corrosion current and less negative potential
  - Fibers DO NOT increase the rate of corrosion

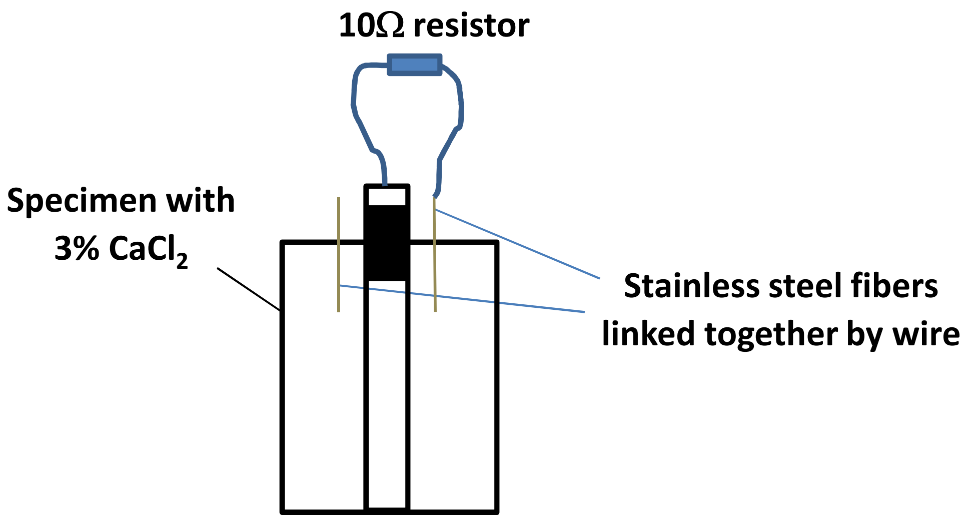


Half-cell potential measurement

Corrosion Behavior of Steel Rebar Surrounded by R2M2 (2/2)

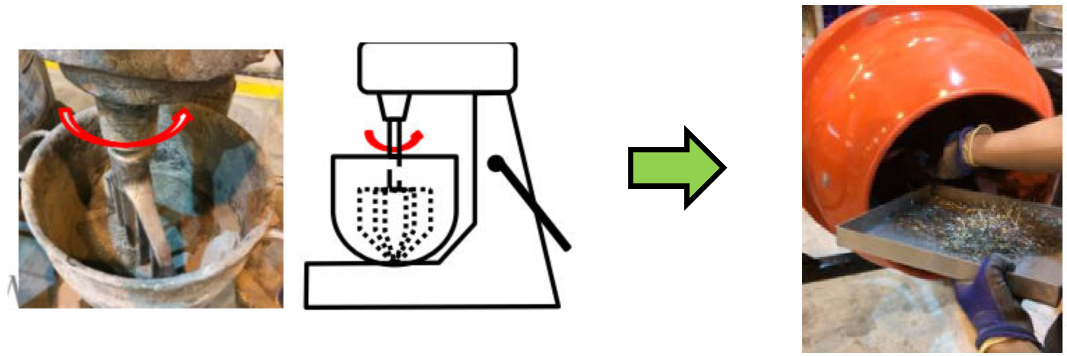
Test 2

- 12 pieces of steel fibers are linked together and then connected to the rebar through a resistor
- Galvanic current measured from potential drop over the resistor
- Galvanic current density is only several per cent of the corrosion current density (for the rebar itself)
  - Galvanic corrosion between rebar and fibers is NOT significant
  - This is likely due to the small cathode/anode area ratio



Proposed Standard Mixing Method for Repair Mortar and Steel Fibers in Practice

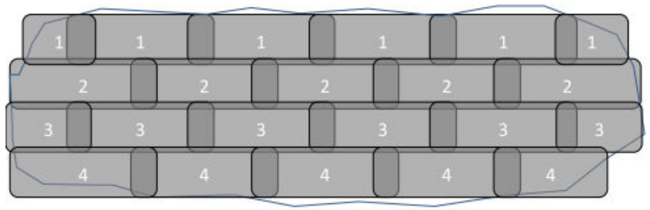
- Dry powder of fixed composition and weight, and a fixed weight of stainless steel fibers, will be packed in separate bags
- In the field, a standard amount of water will be added to the powder, followed by mixing in an electric mixer according to a standard process
- The mortar is then transferred to the drum mixer where fibers are added. Further standard mixing is performed.



Application of Repair Mortar to Hacked Off Area

- Repair mortar is made in a number of strips (e.g. 20mm in diameter and 80mm in length) and placed with the long direction along the existing rebar to enhance fiber alignment along loading direction
- The strips should be patched in a staggered arrangement along the rebar direction, from one end to the other
- Intermediate layers should be keyed and primed before the next layer is applied.
- Similar to conventional practice, care should be taken to ensure all space (including those behind the rebar) are properly filled
- External surface of repair should be leveled with existing surface and be properly finished

R2M2 Strips



Finished Surface

Conclusions and Further Work

- A novel repair method for reinforced concrete slab with corroded steel rebar has been developed
- Specifically, by using fiber reinforced repair mortar, old buildings with 10mm rebar corroded to 60% of its cross section can have its load carrying capacity fully recovered without lapping a new piece of rebar
- Fire resistance of the repair mortar is satisfactory and steel fibers have little effect on rebar corrosion after the repair
- A Public Sector Trial Scheme Proposal is currently under preparation for the conducting of field trials in buildings owned by the Housing Department and Architectural Services Department
    - These studies will allow the optimization of logistics and the development and verification of practical methods for quality control

Acknowledgements

- This study was supported by the Hong Kong Innovation and Technology Commission through the Innovation and Technology Fund
- Matching financial support was provided by Chun Wo Construction and Engineering Limited
- The research was performed in collaboration with the Nano and Advanced Materials Institute Ltd. (NAMI)
- Colleagues from the Hong Kong Housing Department have provided strong support as well as many valuable comments and suggestions to the work