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Seismic Retrofitting Method for Underground Reinforced Concrete Structures by embedding Plate Anchored Shear Reinforcement Bars

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ABSTRACT

There is concern that reinforced concrete (RC) structures designed before the 1995 Hyogo-ken Nanbu Earthquake may lack adequate shear resistance and ductility to withstand the loading of a major earthquake. But retrofitting underground RC structures for greater strength is difficult when there is soil behind the RC, particularly when shear resistance has to be improved. The authors have developed a seismic retrofitting method for such underground RC structures in which shear reinforcement bars, terminated at opposite ends with friction-welded round and rectangular steel plates, are embedded in mortar after drilling the existing RC wall. The procedure increases shear resistance significantly without increasing flexural capacity. This paper covers design of the retrofit, the implementation procedure, experimental verification of the method, and experiments related to applicability of the method to deep beams.

Keywords. Seismic retrofitting, Shear reinforcing, Post-construction, Underground structures, Deep beams

INTRODUCTION

There is a fear that in-service RC structures designed according to old seismic design standards lack shear resistance and ductility to handle major earthquake loading. Seismic retrofitting of such structures is ongoing in Japan. Many methods of retrofitting with a good track record are available for situations where there is all-round access, such as RC lining or thickness-increasing methods, the bonded steel plate method, the bonded fiber method, and the prestressing method. On the other hand, it is difficult to strengthen in-service underground RC structures where there is soil behind the concrete structure. Therefore, there is a need for the development of seismic retrofitting methods specifically aimed at increasing the shear resistance of these structures. The authors have designed such a seismic retrofitting method. This paper describes the design of a retrofit, experimental verification of the method, experiments to demonstrate its applicability to deep beams, and the work implementation procedure.

OUTLINE OF SEISMIC RETROFITTING METHOD

The shear reinforcement bars that are embedded into the structure in this retrofitting method are shown in Photo 1. The bars terminate with a round steel plate at the embedded end and a rectangular steel plate at the exposed internal end; both plates are attached to the bar by friction welding (PWRC, 2011). These bars are embedded in mortar after drilling the existing RC structure. This enables an in-service underground RC structure with soil behind to be strengthened from the inside, as illustrated in Figure 1. The steel plates have the effect of increasing anchorage performance. The rectangular steel plate also plays a role as a spacer to ensure centering of the shear reinforcement in the hole. Since these bars are embedded in the structure, predefined cover is guaranteed and durability is ensured.

Photo 1. Post-construction shear reinforcement bars

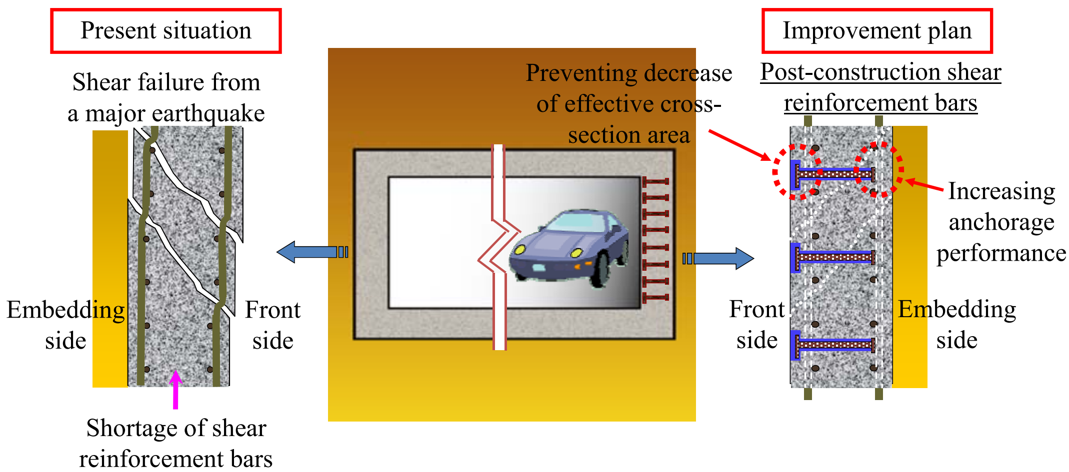


Figure 1. Shear reinforcement using post-construction shear reinforcement bars

IMPLEMENTATION PROCEDURE

Figure 2 shows the procedure used to retrofit a structure with post-construction shear reinforcing bars. The major steps are described below.

Step 1: Positioning for Drilling

Drilling positions for the post-construction shear reinforcement bars are selected using radar or another method such that existing rebars are avoided.

Step 2: Drilling

Holes for the interpolated post-construction shear reinforcement bars are drilled from inside the structure. Subsequently, the holes are reamed or expansion drilled to a suitable depth to take the rectangular plate. A standard venture drill is used for drilling in consideration of construction efficiency. The merits of using this drilling method are: (1) no danger of cutting existing rebar, since this is not a cutting method, (2) no use of water, (3) ability to inhibit dust by using a dust collector, (4) small, lightweight equipment allowing manual operation, (5) ability to work in small spaces, and (6) rapid drilling.

Step 3: Mortar Packing and Post-construction Reinforcement Bar Placement

After drilling, the hole is cleaned and moistened. A hand pump is then used to completely fill the hole with mortar. The post-construction shear reinforcement bar is then inserted and any expelled mortar is cleaned away.

Step 4: Patching Repair

Finally, the structure is patched by filling the expansion-drilled part of the hole with repair material.

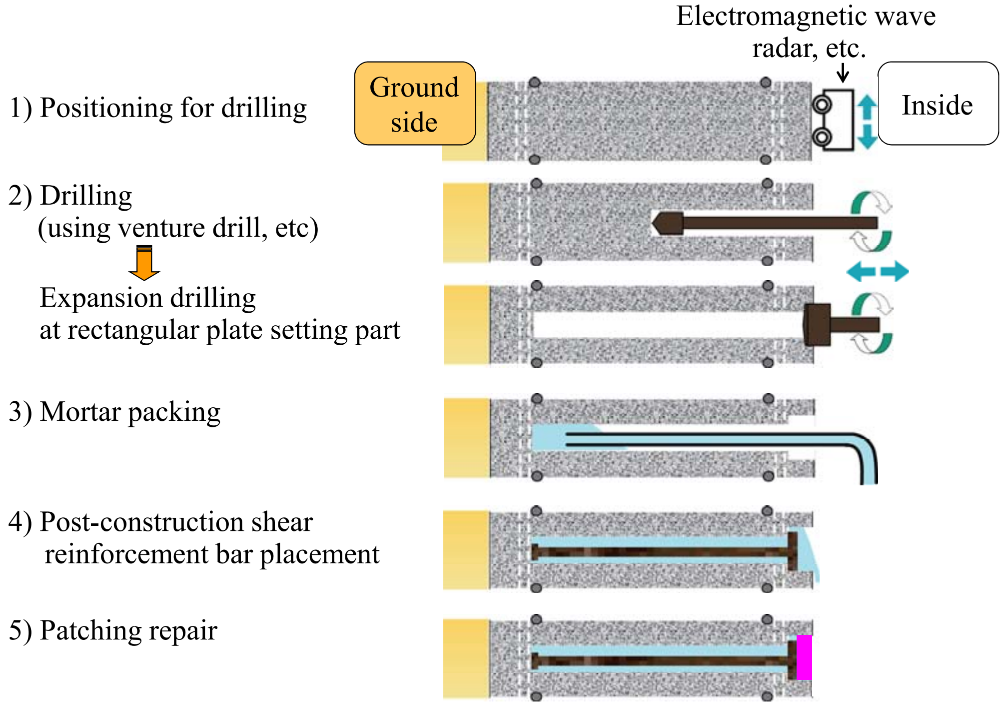


Figure 2. Implementation procedure

RETROFITTING DESIGN METHOD

Verification of Shear Reinforcing Effect

An experiment was carried out to verify the strengthening effect of this retrofitting method on an RC wall subject to out-of-plane shear force. Figure 3 outlines the experiment. Static reverse cyclic loading was applied to two RC beam specimens using two supports and two loading points. Each specimen was 4,100mm long with a span of 3,600mm. In case-A, the specimen had no shear reinforcement bars in the shear span. In case-B, two post-construction shear reinforcement bars of size D16 were embedded 200mm apart in the longitudinal direction of the shear span.

Figure 4 shows the load-displacement relationships for the specimen beams. Table 1 compares the shear capacity as obtained by experiment and by calculation. The calculations were based on Standard Specification for Concrete Structures (JSCE, 2007) using the real strength of the concrete and rebars. From the experimental result, it is clear that the shear capacity of Case-B far exceeds that of Case-A. This confirms that shear capacity is increased by this retrofitting method. Since in 90% of the cases shear reinforcement are preliminarily embedded, this retrofitting method has sufficient strengthening effect.

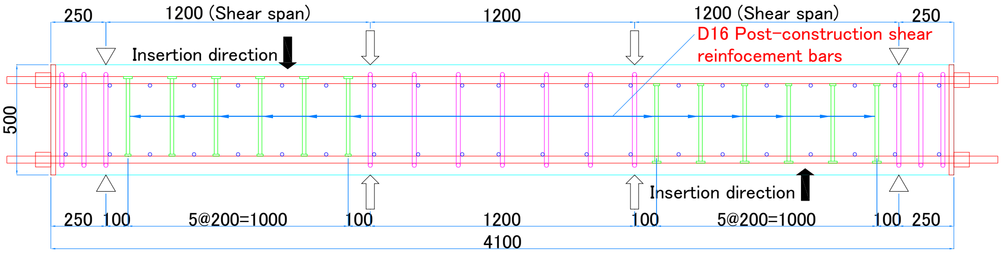
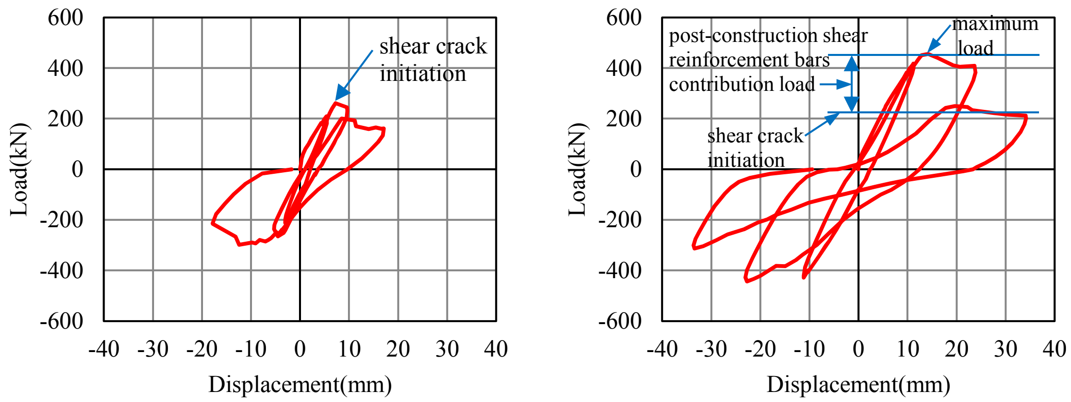


Figure 3. Outline of experiment (Case-B)



(a) Case-A **(b) Case-B**

Figure 4. Load-displacement relationships

Table 1. Experimental results and effectiveness factor

Experiment case			Case-A	Case-B
Shear capacity	Experiment Vexp(kN)		261	486
	Calculation Vcal(kN)	Concrete Vcd(kN)	241	230
		Shear reinfocement bars Vawd(kN)	-	286
		Vcal=Vcd+Vawd(kN)	241	516
Contribution of post-construction shear reinforcement bars to shear capacity Vawd,exp(kN)=Vexp-Vcd			-	256
Effectiveness factor of shear capacity β	By experiment Vawd,exp/Vawd		-	0.90
	By Formula (1)		-	0.89

Formulation of Shear Reinforcing Effect

Assume that the tensile stress distribution that can be borne by the shear reinforcement bars is as given by the anamnestic evaluation method (JSCE, 2005) as shown in Figure 5. At the rectangular plate end, it has the anchorage capability to the edge of the rebar sufficiently just as with a normal semicircular hook. On the other hand, at the round plate end, transmissive stress depends on the relationship between the anchorage length and the distance from the shear crack to the outer surface of the shear reinforcement bar. Therefore, the effectiveness factor representing the increment in shear capacity using this retrofitting method as compared with the unmodified case is the area of the transmissive stress distribution, as shown in Figure 5 and calculated by Formula (1). Anchorage length l_y of round plate side is defined to 5.0D (D: diameter) from the results of confirmation tests of anchorage length (PWRC, 2011).

$$\beta_{aw} = 1 - \frac{l_y}{2(d - d')} \qquad (1)$$

where, β_{aw}: reinforcing effectiveness factor, l_y: anchorage length, and d-d’: distance between compressive and tensile reinforcement, where d-d’>l_y.

The calculated effectiveness factor for the experimental conditions is 0.89, while that determined by experiment is almost the same, as shown in Table 1.

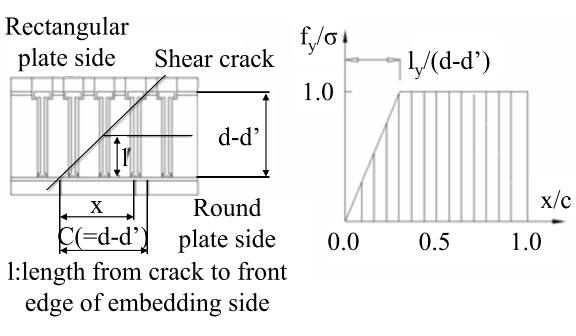


Figure 5. Stress distribution of post-construction shear reinforcement bars in shear crack

Evaluation of Retrofitted Shear Capacity

The shear capacity of a member strengthened using this retrofitting method is calculated using Formulas (2) and (3) based on the Standard Specification for Concrete Structures (JSCE, 2007).

$$V_{pyd} = V_{cd} + V_{sd} + V_{phd} \qquad (2)$$

where, V_{pyd}: shear capacity of member, V_{cd}: concrete contribution to shear capacity, V_{sd}: contribution of existing shear reinforcement bars to shear capacity, V_{phd}: contribution of retrofitted shear reinforcement bars to shear capacity.

$$V_{phb} = \beta_{aw} \cdot V_{awd} \qquad (3)$$

where, β_{aw}: effectiveness factor of shear capacity, V_{awd}: shear capacity of shear reinforcement bars assuming normal retrofitting.

Experimental Determination of Effectiveness Factor

Loading tests were carried out on beam specimens designed with thick D29 (SD345) rebar so as to ensure shear failure and using high-strength SD390 (D25) rebar for the retrofitted shear reinforcement. The experimental method is the same as that outlined in Figure 3. Table 2 shows the specifications of the beam specimens and the experimental results. In each case, the shear improvement effectiveness factor as found in the experiment is the same as or greater than that calculated by Formula (1). This means that the shear improvement effectiveness factor when using this retrofitting method can be calculated using

Table 2. Experimental results and effectiveness factor

<table>
<tr><td colspan="3">Experiment case</td><td>Case-1</td><td>Case-2</td><td>Case-3</td><td>Case-4</td></tr>
<tr><td colspan="3">Section(mm×mm)</td><td colspan="4">800×800</td></tr>
<tr><td colspan="3">Shear span(mm)</td><td>2000</td><td>1450</td><td>2000</td><td>2000</td></tr>
<tr><td colspan="2" rowspan="2">Post-construction shear reinforcement bars</td><td>Diameter and material</td><td colspan="3">D29
SD345</td><td>D25
SD390</td></tr>
<tr><td>Arrangement</td><td colspan="2">@350×400
(parallelism)</td><td>@350×400
(zigzag)</td><td>@350×400
(parallelism)</td></tr>
<tr><td rowspan="4">Shear capacity</td><td colspan="2">Experiment Vexp(kN)</td><td>1405</td><td>1265</td><td>1245</td><td>1135</td></tr>
<tr><td rowspan="3">Calculation Vcal(kN)</td><td>Concrete Vcd(kN)</td><td>389</td><td>397</td><td>395</td><td>407</td></tr>
<tr><td>Shear reinfocement bars Vawd(kN)</td><td>876</td><td>876</td><td>876</td><td>807</td></tr>
<tr><td>Vcal=Vcd+Vawd(kN)</td><td>1265</td><td>1273</td><td>1271</td><td>1214</td></tr>
<tr><td colspan="3">Contribution of post-construction shear reinforcement bars to shear capacity Vawd,exp(kN)=Vexp-Vcd</td><td>1016</td><td>868</td><td>850</td><td>728</td></tr>
<tr><td colspan="2" rowspan="2">Effectiveness factor of shear capacity β</td><td>By experiment Vawd,exp/Vawd</td><td>1.00(*1)</td><td>0.99</td><td>0.97</td><td>0.90</td></tr>
<tr><td>By Formula (1)</td><td>0.86</td><td>0.86</td><td>0.86</td><td>0.88</td></tr>
</table>

(*1)Vawd,exp/Vawd>1.0→1.0

Formula (1). The upper limit of the factor is set at 0.9 so as to give a safety margin. The formula includes a parameter of anchorage length as a function of diameter and material. This is defined to the range 3.5D-5.5D (D: diameter) from the results of confirmation tests of anchorage length (PWRC, 2011).

STUDY ON APPLICABILITY OF RETROFITTING METHOD TO DEEP BEAMS

When the shear span ratio is small, such as in footings, the members are called deep beams. The shear force resistance mechanism in such members differs from that in typical bar members because the shear span ratio is relatively large. It is known that when stirrups are used in deep beams, their shear reinforcing effect is less than that given by truss theory, though they have a certain degree of strengthening effect. (Tanimura *et al*. 2004) Therefore, in order to study the strengthening effect of the retrofitted shear reinforcement bars in the case of deep beams, loading tests of deep beam specimens were carried out.

Figure 6 shows an outline of the experiment. Shear reinforcement bars (D16) are embedded 237.5mm apart in a longitudinal direction in the shear span. These shear reinforcement bars are semicircular hook type ones in Case-a and retrofitted ones in Case-b. Figure 7 shows the load-displacement relationships of the specimens. Table 3 compares the shear capacity as given by experiment and calculation, where the calculated values are obtained based on an experimental formula (Tanimura *et al*. 2004) that is the basis of the formula given in the Standard Specification for Concrete Structures (JSCE, 2007) using the real strength of concrete and rebar. For both cases, the experimental value is higher than the calculation, with the ratio of experimental to calculated value falling in the same range. In Case-b, after flexural compression failure occurred the load increased once again, but shear capacity is defined as the load at the point where the load first decreased in flexural compression failure. This experimental result demonstrates that deep beam members strengthened using this retrofitting method gain equivalent shear capacity as members constructed with semicircular hook type shear reinforcement bars.

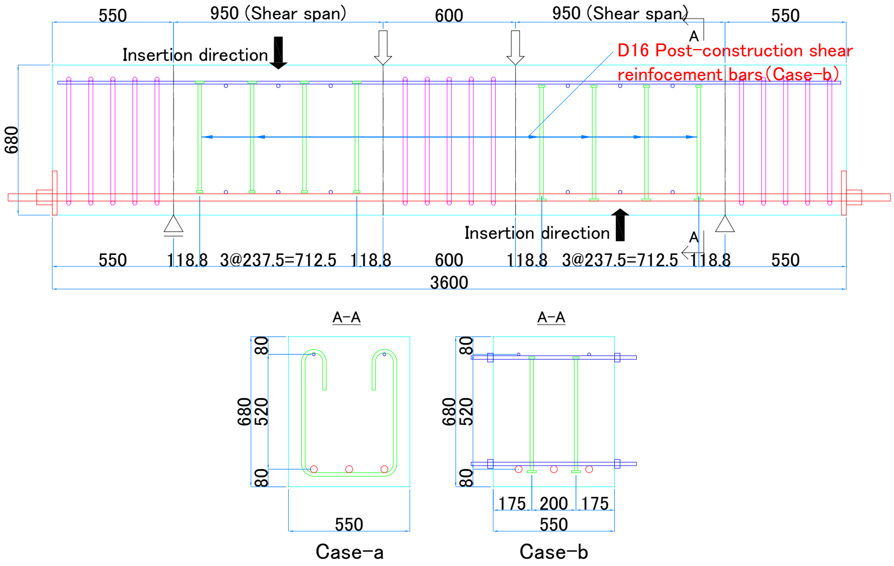


Figure 6. Outline of experiment

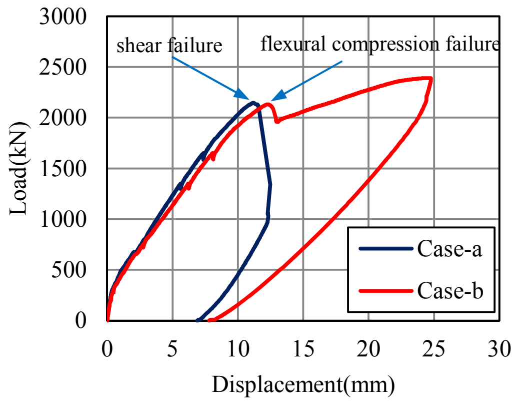


Figure 7. Load-displacement relationships

Table 3. Experimental results

Experiment case			Case-a	Case-b
Shear span ratio a/d			1.58	
Type of shear reinforcement bars			semicircular hook type	Post-construction shear reinforcement bars
Diameter and arrangement			D16@237.5mm	
Shear reinforcement ratio(%)			0.30	
Compressive strength f'c(N/mm^2)			34.0	32.8
Shear capacity	Experiment Vexp(kN)		2147	2131
	Calculation Vcal(kN)	Concrete Vcd(kN)	1367	1335
		Shear reinforcement bars Vawd(kN)	651	636
		Vcal=Vcd+Vawd(kN)	2018	1971
Contribution of shear reinforcement bars to shear capacity Vawd,exp(kN)=Vexp-Vcd			780	796
Ratio of experimental to calculation	By experiment Vawd,exp/Vawd		1.20	1.25

CONCLUSIONS

A seismic retrofitting method has been developed for application to in-service underground RC structures where there is soil present behind the structure. The increased shear capacity brought about by this retrofitting method has been verified through experiment. The improvement in shear capacity of a member strengthened by this retrofitting method can be calculated using Formulas (2) and (3). Furthermore, additional experiments have shown that the shear improvement effectiveness factor of this retrofitting method can be calculated using Formula (1). An upper limit of 0.9 is established for this factor so as to ensure a suitable safety margin. Finally, experiments on deep beam members show that strengthening by this retrofitting method provides them with equivalent shear capacity to semicircular hook type shear reinforcement bars.

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