Emergency Retrofit of Shear Damaged Extremely Short RC Columns Using Pre-tensioned Aramid Fiber Belts

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Abstract

The seismic retrofit of existing RC buildings, which are vulnerable to seismic excitation, remains an active area of research. Emergency retrofit is necessary for rehabilitation of damaged RC buildings immediately after earthquake occurrences. The emergency retrofit technique is a laborsaving, quick and dry process. From such viewpoints, an emergency retrofit of RC columns damaged in earthquakes is proposed in this study. The pre-tensioned aramid fiber belt acts as a shear strengthening element as well as an axial capacity recovery method since the belt provides transverse confinement for the column. The retrofit method sufficiently recovers the earthquake performance as long as the damage caused by the earthquake is within the moderate level and the column can sustain the vertical load.

1. Introduction

The Japanese islands may be called a natural shaking table. In 1995, the destructive damages in the Great Han-shin Awaji Earthquake (AIJ 1995) have revealed the fact that the majority of buildings in regions of high seismicity in Japan are vulnerable to damage and collapse in the case of an earthquake, as many of these buildings do not meet current seismic design code requirements. As a result, the Law for Promotion of Seismic Retrofit was enforced in 1995 to promote the seismic capacity evaluation and rehabilitation of existing buildings (Otani 2003). This law recommends owners of specific buildings utilized by a large number of persons to carry out seismic vulnerability assessments and retrofit. At present, seismic vulnerability assessments of specific public buildings such as schools, government offices, hospitals and police stations are carried out in various parts of Japan. Seismic retrofit of the existing buildings diagnosed as requiring this action is gradually being carried out in Japan.

Seismic retrofit uses fundamental methods to increase the strength and ductility of buildings. Several retrofit methods control the seismic response of buildings. For example, base-isolation reduces the seismic input while vibration control devices increase the energy absorption capacity. For such situations, ductility type of the seismic retrofit for the independent RC column in which prestress is applied using high-strength steel rods, was proposed by T. Yamakawa and M. Kurashige et al. (Yamakawa et al. 2000; Yamakawa et al. 2001a; Yamakawa et al. 2003). This type of reinforcement is also utilized in RC column attached with secondary walls such as spandrel walls and wing walls. Simultaneously T. Yamakawa started to develop the permanent/emergency seismic retrofit method, which uses pre-tensioned aramid fiber belts instead of high-strength steel rod prestressing (Yamakawa et al. 2001b; Satoh et al. 2001; Nasrolahzadeh et al. 2002; Yamakawa et al. 2002).

Permanent seismic retrofit and strengthening are important actions to ensure structure resistance to earthquakes. However, emergency retrofit for damaged RC columns right after the occurrence of an earthquake also has an important role to play. The collapse of a building can be prevented by emergency retrofit, if the columns can continue sustaining vertical loads over the long term after the damage caused by an earthquake. Therefore, the emergency retrofit of damaged columns is important. Moreover, emergency retrofit ensures good seismic performance of the damaged building in the case of aftershocks, allowing residents to continue inhabiting the building. The building owners can then choose to perform permanent seismic strengthening, rehabilitation work, or rebuilding after the complete end of aftershocks. The damage level and cost are among the main factors considered in making a decision. In this study, emergency retrofit for ensuring seismic performance and safety of buildings damaged in earthquakes is proposed. The emergency retrofit consists in firmly embedding steel plates on the surfaces of damaged columns fitted with pre-tensioned aramid fiber belts.

In this study, the effectiveness of this emergency retrofit is discussed with regard to the following four aspects: 1) Repairable damage level of the damaged RC columns, 2) Survival of axial compression capacity of the damaged RC columns, 3) Seismic performance after the application of emergency retrofit to the damaged RC columns, and 4) Effect of the pre-tension force applied to aramid fiber belts. By clarifying these four aspects, the

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design details of emergency retrofit of RC columns damaged in earthquakes will be established. The aramid fiber belt is simply referred to as “belt” hereafter.

2. Test plan

The details of emergency retrofitted specimens are listed in Table 1. The mechanical properties of reinforcing steel, steel plate and aramid fiber belt (17 mm width, 0.612 mm thickness) used in this experiment are shown in Table 2. The size of the column specimens is 250 × 250 × 500 mm. The shear span to depth ratio (M/(VD)) is 1.0 (Fig. 1). The specimens are the shear failure type due to the insufficient transverse reinforcement (pw = 0.08%). The flowchart of the loading test carried out as a combination of cyclic lateral forces and a constant axial force (axial force ratio = 0.2) is shown in Fig. 2. In order to discuss the effect of different damage levels, the first cyclic loading test was carried out for two different cases. In one case, the lateral load was applied for 3 cycles of drift angle of 0.5% and in the other case for 1 cycle of drift angle of 1.0% in addition to 3 cycles of drift angle of 0.5%. The former case was applied to specimens ER03S-Aw65SN and ER03S-Aw65S, and the later case was applied to specimens ER02S-Aw65S2 and ER02S-Aw65S3 (Fig. 6). In both cases, the damage was generated by shear failure. By returning the horizontal force to zero right after the shear failure, the residual axial compression capacity of the damaged column was measured in specimens ER03S-Aw65SN and ER03S-Aw65S, in other words only the ER03S series of specimens, as shown in Table 1.

The emergency retrofit using pre-tensioned aramid fiber belts and steel plates (t = 3.2 mm) was conducted as a second step, while the axial force (axial force ratio = 0.2) still existed during retrofitting. In the ER03S series of specimens, the sustainable vertical force after damage in shear was measured as outlined in Fig. 2. Afterwards, the cyclic horizontal loading test was carried out again under the constant axial compression (axial force ratio = 0.2). However, the cyclic loading test of specimen ER02S-Aw65S3 was carried out by increasing the axial force.

### Table 1 Details of emergency retrofitted specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>ER03S-Aw65SN</th>
<th>ER03S-Aw65S</th>
<th>ER02S-Aw65S2</th>
<th>ER02S-Aw65S3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel plate</td>
<td>Steel plate</td>
<td>Steel plate</td>
<td>Steel plate</td>
<td></td>
</tr>
<tr>
<td>M/(VD)=1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Max. crack width</td>
<td>0.95mm (small)</td>
<td>1.0mm (small)</td>
<td>7.0mm (medium)</td>
<td>5.0mm (medium)</td>
</tr>
<tr>
<td>Pre-tension strain level</td>
<td>0µ</td>
<td>3500µ (413MPa)</td>
<td>7000µ (826MPa)</td>
<td></td>
</tr>
<tr>
<td>Axial force ratio</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>σB</td>
<td>28.5 MPa</td>
<td>23.9 MPa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aramid fiber belt</td>
<td>2ply-double-@65</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Common details</td>
<td>Longitudinal reinforcement: 12-D10 (pg=1.36%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transverse reinforcement: 3.7φ-@105 (pw=0.08%)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: σB=concrete cylinder strength

### Table 2 Mechanical properties of materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>a (mm²)</th>
<th>t (mm)</th>
<th>σu, σy (MPa)</th>
<th>εu, εy (%)</th>
<th>E (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aramid belt (Single belt)</td>
<td>a</td>
<td>10.4</td>
<td>σu</td>
<td>2065</td>
<td>εu</td>
</tr>
<tr>
<td>Steel plate (t=3.2mm)</td>
<td>t</td>
<td>3.2</td>
<td>σy</td>
<td>276</td>
<td>εy</td>
</tr>
<tr>
<td>Rebar (D10)</td>
<td>a</td>
<td>71.0</td>
<td>σy</td>
<td>372</td>
<td>εy</td>
</tr>
<tr>
<td>Hoop (3.7φ)</td>
<td>a</td>
<td>11.0</td>
<td>σy</td>
<td>390</td>
<td>εy</td>
</tr>
</tbody>
</table>

Note: a=cross section area, t=thickness, E=modulus of elasticity, σu=tension design strength, σy=tension yield strength, εu=tension design strain, εy=tension yield strain.
force ratio from 0.2 to 0.4. Photographs of shear failure specimens before and after emergency retrofit are shown in Fig. 3. Upon completion of the cyclic loading test of the retrofitted specimens for one cycle of drift angle of 5.0%, the residual axial compression capacity was measured only for the ER03S series of specimens.

Belts for the emergency retrofit are wound in parallel using double width belts of 17 mm width onto the damaged column. Each belt is impregnated with epoxy resin along only a 100 mm lap joint at both cut ends to form a loop, which is straightened to form a two-ply belt. Both ends of each two-ply double belt, after being straightened, look like an eye-hook, through which a crossbar can be passed. When the two-ply double belts are wound around the column, their ends can be clamped together by putting a couple of crossbars into the end eye-hooks, and then passing bolts through the threaded hole of the crossbar. Steel angles, which are located at the corners of the column, are 50 mm wide and long and 20 mm thick. An external radius of 20 mm is provided for the corner angle. In this study, the belts were not impregnated with epoxy resin except for the part where strain gauges were attached to the belt. Pre-tension force can be applied to the belts by manually screw driving the bolts of the crossbars. The applied pre-tension strain was approximately 7,000 µ in ER02S series specimens and approximately 3,500 µ in specimen ER03S-Aw65S. In specimen ER03S-Aw65SN, no pre-tension force was applied to the belt. The belt interval was 65 mm for all specimens. Steel plates (470 × 240 × 3.2 mm) were embedded firmly on each surface of the damaged column to provide protection against spalling of the cover con-

![Fig. 2 Flowchart of loading test.](image)

![Fig. 3 Column specimen.](image)

![Fig. 4 Details of retrofit technique.](image)
crete and buckling of the longitudinal reinforcement except corner reinforcement. The steel plates also act as shear reinforcement and transverse confinement. The assembly of a couple of crossbars and bolts, as shown in Fig. 4, is referred to as a coupler.

Figure 5 shows the test setup and loading program. This loading apparatus can simultaneously apply cyclic lateral forces and constant axial compression. Lateral loading cycles include three successive cycles at each drift angle with the values of $R = 0.5, 1.0, 1.5, 2.0, 2.5$ and $3.0\%$. To investigate the elastoplastic behavior under large deformation, the loading test was continued for drift angle values $R = 4\%$ and $5\%$ for one cycle each.

### 3. Test results

Figure 6 illustrates the crack patterns and maximum crack width right after the shear failure at the first cyclic loading test for the specimens prior to retrofit, as well as the crack patterns of the emergency retrofitted specimens after the final cyclic loading test. Typical shear cracks can be observed on the RC column specimens before the emergency retrofit. The shear cracks did not progress following emergency retrofit using belts. On the contrary, flexural cracks were generated. This fact indicates that the emergency retrofit transfers the failure mode from shear to flexure (Fig. 7). The hysteresis loops on shear force $V$ and drift angle $R$ of the specimens, and the relation between the average axial strain and drift angle of the column are presented in Fig. 7. The dotted line drawn in the $V$-$R$ curve is the calculated flexural strength with the AIJ simplified equation. The flexural strength was calculated considering the $P$-$\delta$ effect, while the transverse confinement effect of the belt was disregarded. The maximum crack width of the specimens of the ER03S series until $R = 0.5\%$ with three successive cycles was approximately 0.95 to 1.0 mm (Fig. 6). Afterwards, the lateral force was released but the axial force was maintained in order to measure the residual axial compression capacity of the damaged test specimens. The residual axial capacity can be accurately confirmed if the axial force is continuously increased until the damaged col-

<table>
<thead>
<tr>
<th>ER03S-Aw65SN</th>
<th>ER03S-Aw65S</th>
<th>ER02S-Aw65S2</th>
<th>ER02S-Aw65S3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before retrofit</td>
<td>After final loading</td>
<td>Before retrofit</td>
<td>After final loading</td>
</tr>
<tr>
<td><img src="image1" alt="Crack Pattern" /></td>
<td><img src="image2" alt="Crack Pattern" /></td>
<td><img src="image3" alt="Crack Pattern" /></td>
<td><img src="image4" alt="Crack Pattern" /></td>
</tr>
<tr>
<td>$R=0.5%$</td>
<td>$R=0.5%$</td>
<td>$R=0.5%, R=1.0%$</td>
<td>$R=0.5%, R=1.0%$</td>
</tr>
<tr>
<td>3 cycles</td>
<td>3 cycles</td>
<td>3 cycles, 1 cycle</td>
<td>3 cycles, 1 cycle</td>
</tr>
<tr>
<td>(0.95 mm)</td>
<td>(1.0 mm)</td>
<td>(7.0 mm)</td>
<td>(5.0 mm)</td>
</tr>
</tbody>
</table>

( )=Max. crack width
umn is destroyed by compression. However, in this case, the loading was stopped at an axial force ratio of approximately 0.5, because too extensive a damage would make retrofitting impossible. Afterwards, the axial force was returned at axial force ratio of 0.2. Then the ER03S series specimens were emergency retrofitted with steel plates and pre-tensioned aramid fiber belts at axial force ratio of 0.2. The axial strength of the emergency retrofitted specimens recovered to the cylinder strength of RC column concrete. However, the recovery of specimen ER03S-Aw65SN was possible to only approximately 80% of the cylinder strength of RC column concrete, because the pre-tension force was not applied to the belt. As a result of emergency retrofitting, the emergency retrofitted specimens showed stable behavior and no degradation in lateral capacity during the reversed cyclic loading test. The average axial strain of the column was also recovered. The axial compression capacity was also measured upon completion of the cyclic loading test. The compressive strength has ensured almost the same concrete strength as an RC column (Fig. 9).

In ER02S series specimens, large shear cracks were generated and degradation in lateral capacity occurred after 1 cycle of drift angle \( \Delta R = 1.0\% \) in addition to 3 cycles of \( \Delta R = 0.5\% \) under constant axial force ratio of 0.2, and the maximum crack widths were 7.0 mm and 5.0 mm, respectively. Afterwards, the above-mentioned emergency retrofit was conducted without confirming residual axial capacity, and the cyclic loading test was carried out again under constant axial force ratio of 0.2. The axial force ratio was increased from 0.2 to 0.4 to investigate the effect of the different axial force ratio after emergency retrofit on ER02S-Aw65S3 only. As a result, the lateral capacity reached the calculated flexural strength at \( \Delta R = 1.5-2.0\% \) and gradually increased until \( \Delta R = 5.0\% \). Since the initial damage of the column before emergency retrofit was large, the compressive strain was dominant for the average axial strain of column specimen ER02S-Aw65S2. In specimen ER02S-Aw65S3, the compressive strain was generated in the average axial strain of the column, since it was subjected to high axial force in addition to large initial damage.

The test results showed that the emergency retrofit with steel plates and pre-tensioned belts drastically re-
covers seismic performance. It can be judged that the emergency retrofit is effective even at high axial force ratio of 0.4. The variations of fiber belt strains with drift angles during cyclic loading tests are shown in Fig. 8. The dotted line shown in Fig. 8 is the initial pre-tension strain applied to the belt. The application of prestress shows better recovery performance of specimen ER03S-Aw65S than that of specimen ER03S-Aw65SN when the damage levels of both are almost equal. Initial pre-tension strain (3,500 \( \mu \)) in the belt of specimen ER03S-Aw65S slightly increased. On the other hand, the belt strain of specimen ER03S-Aw65SN increased as the drift angle increased. When the cyclic loading test was carried out again after applying the emergency retrofit, the applied pre-tension strain in the belts declined a little because of existence of large damage due to shear failure in the ER02S series.

4. Axial capacity and constitutive laws

The maximum compression stresses resisted by shear damaged specimens of the ER03S series during the axial compression test before and after retrofit are listed in Table 3. In the damaged specimens, the axial compression capacity obtained in each compression test is a moderate value, because axial force is not applied until specimen destruction by compression. If the specimen is completely destroyed by the axial compression test, emergency retrofit for this damaged specimen is impossible. The axial compression test results of shear damaged RC column specimens of the ER03S series on three occasions are illustrated in Fig. 9. The vertical axis in Fig. 9 represents the axial force (N) and the horizontal axis represents the average axial strain (\( \varepsilon_v \)) of the RC column. The axial compression force carried by the concrete is given by deducting the axial force carried by the longitudinal reinforcement. It is assumed that the longitudinal reinforcement strain is equal to the average axial strain of the column. However, the yield strength was used for the case in which the average axial strain exceeded the yield strain of the longitudinal reinforcement. Since true peak axial force cannot be obtained from Fig. 9, Mander’s equation in constitutive law of confined/unconfined concrete (Mander et al. 1988) is applied to the axial compression test results in Fig. 9. As a result, the stress-strain relationships of confined/unconfined concrete can be illustrated as shown in Fig. 10.

The flexural and shear strength of emergency retrofitted column specimens of ER03S series were calculated (Fig. 10) using the values shown in Table 3. A comparison of these calculated values and the skeleton curves based on cyclic loading tests is shown in Fig. 11. The yield level was confirmed through axial compression testing of specimen ER03S-Aw65SN after applying emergency retrofit (Fig. 9) and the concrete strength obtained from the test result matched the strength obtained from the test and the calculated result, as shown in Table 3. The flexural strength of specimen ER03S-Aw65SN calculated using this experimental value agreed with the cyclic loading test results at R = 5% (Fig. 11), because passive lateral confinement becomes more effective as the drift angle increases. On the other hand, in specimen ER03S-Aw65S, the yield level was not confirmed after the emergency retrofit in the axial compression test and hence, the calculated results using this experimental value are higher than the test results. According to the axial compression test and Mander’s model, the compressive concrete strength of

<table>
<thead>
<tr>
<th>Test result (concrete &amp; rebar)</th>
<th>Test result (concrete only)</th>
<th>Test &amp; calculated result (concrete only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before retrofit</td>
<td>After retrofit</td>
<td>Before retrofit</td>
</tr>
<tr>
<td>ER03S-Aw65SN</td>
<td>14.2</td>
<td>22.5</td>
</tr>
<tr>
<td>ER03S-Aw65S</td>
<td>12.7</td>
<td>29.0</td>
</tr>
</tbody>
</table>
specimen ER03S-Aw65S was estimated as 25.7 MPa. The flexural strength calculated using this value agrees well with the experimental result (Fig. 11). It was proven that the lateral capacity could be almost estimated in the measurement of the axial compression test. The damage level of specimens ER03S-Aw65S and ER03S-Aw65SN is nearly equal. There is a difference of 8.3 MPa between the confined concrete strength of 25.7 MPa for specimen ER03S-Aw65S and that of 17.4 MPa for specimen ER03S-Aw65SN. This difference is the active confinement effect due to the pre-tension force in the belt. This fact proves that the application of pre-tension force in emergency retrofit is very effective.

5. Analytical investigation

A comprehensive and nonlinear analytical investigation was carried out based on a state-of-the-art analytical model using the fiber model technique considering both flexural deformation and shear distortion (Banazadeh et al. 2004a; Banazadeh et al. 2004b). This model was established based on the combination of the fiber technique and the Modified Compression Field Theory (MCFT) (Vechio et al. 1986). The main feature of this model is that the nonlinear shear distortion is added to the flexure model in a series, as an uncoupled force-deformation relation, on the basis of a flexibility formulation. The flexural deformation is based on a conventional fiber section concept with a distributed plasticity in which the hysteretic rules of reinforcing steel and concrete are those presented in existing literature (Menegotto et al. 1973) and (Mander et al. 1988), respectively (Fig. 13). However, the buckling of the main reinforcement is disregarded, because the effect is small in this case (Menegotto et al. 1973). In this flexural analysis, the $M-\phi$ curve is calculated along the member axis in several monitoring sections within an iterative procedure by finding out the appropriate curvature condition that satisfies the external force diagram, as shown in Figs. 12 and 13. The bending moment based on the $M-\phi$ curve at each fiber section must be satisfied with the bending moment at the corresponding section obtained from the linear bending moment distribution of the column member. Next, the curvature distribution is obtained along the member axis, and the flexural deformation is calculated by the application of the principle of virtual work.

The shear effects as another source of deformation are considered based on an explicit relation between shear force and shear distortion with a calibrated hysteretic rule (Fig. 13) (D’Ambris et al. 1999). This model consists of a concentrated translation spring of zero dimensions located at each member end. The two springs are connected by an infinitely rigid bar to form the flexibility coefficient of shear deformation (Fig. 12). Still, the skeleton curve of the shear is required through further modification of MCFT (Vechio et al. 1986). This is because the accuracy of MCFT is not good when the shear...
span to depth ratio is lower than 2.5. The monotonic backbone curve of the shear force-distortion relation is initially calculated by MCFT. In order to improve the shear force-distortion relation derived by MCFT, a modification procedure based on experimental data is also applied (Banazadeh et al. 2004b). Using this modification method, the shear force-distortion relation is parallel to the original MCFT for strength softening, but the distortion corresponding to shear strength is a fixed value of 0.4%. This value is based on a correlation study performed on a number of shear critical column specimens at the University of the Ryukyus (Yamakawa et al. 2000) and also based on suggestions by Tomii and Takeuchi (Tomii et al. 1968). The shear strength also can be adopted based on AIJ, Modified Arakawa, or any other simplified equation (AIJ 1999). The failure mode can be predicted by applying MCFT to RC columns. Namely, if the skeleton curve after the peak shear stress is in a descending branch, shear failure will be generated. An ascending branch would suggest flexural failure as illustrated in the shear effect in Fig. 13. The general hysteretic model suggested by Filippou (D’Ambrisi et al. 1999) was calibrated based on cyclic loading tests to take into account pinching and strength degradation for the shear effect. Using this model combined with the fiber technique, an elastoplastic analysis of RC columns emergency retrofitted with pre-tensioned aramid fiber belts for earthquake resistance was performed.

By adding flexural deformation and shear distortion, the relationship between horizontal displacement and horizontal force, namely the shear force of the column, is obtained. However, it is difficult to obtain the result at one time, because this calculation process is entirely nonlinear. The calculation of deformation in one step requires iterative calculation of the flexural deformation and shear distortion. In the convergence calculation, the Newton-Raphson method is repeatedly utilized, and the calculation volume is enormous. The details of this new analytical model are available in the existing literature (Banazadeh et al. 2004b). Combination of nonlinear curvature distribution along the member axis with a nonlinear shear force-average shear distortion is the main feature in this analytical model. Since the shear effects are considerable in the case of RC members with a small shear span to depth ratio, considering the shear effects improves the accuracy of analytical simulation using the fiber model.

Numerical examples of RC column specimens before and after retrofit are shown in Figs. 14 and 15. Non-retrofitted short RC column specimen generated a brittle shear failure due to poor transverse reinforcement as the result of cyclic loading tests under constant vertical load (axial force ratio = 0.2). However, when the seismic retrofit was applied to the short RC column using aramid fiber belt prestressing, a ductile flexural failure happened as shown in Figs. 14 and 15. The specimens with a shear span to depth ratio of 1.0 were analyzed using the method described above. The analytical results are illustrated and are compared with the experimental results in Figs. 14 and 15. Both results agree well. The $\varepsilon_v$ is the average axial strain along the member axis of the column specimen. In spite of axial compression force, tension strain $\varepsilon_v$ in specimen ER03S-Aw65S appears as the drift angle increases and its analytical result agrees well with experimental result. In addition, the contributions of analytical flexural and shear lateral deformations in the total skeleton curve of all specimens are compared in Figs. 14 and 15. Generally, in the very early stage of the $V$-R relation and before yielding of the longitudinal reinforcements, the contribution of shear displacement is more pronounced than that of flexural displacement. Following the application of emergency ret-

![Figure 12](image-url)

Fig. 12 General force and deformation in nonlinear reinforced concrete column.
CDE: Partial unloading and reloading

**KOS**: Complete unloading and reloading including pinching

**GHI**: Complete unloading and reloading including pinching

**KO** and **GH** are soft central region where shear sliding occurs,

**O** and **H** are crack closing points corresponding to \( V^\text{cr} \) and \( V^\text{cr} \)

* ABC is monotonic which is initially based on modified compression field theory and is then improved in this paper.

** Unloading and reloading are done according to hysteretic rule proposed by Filippou.

Shear hysteretic model (D’Ambrisi et al. 1999)

- Modified MCFT
- ** MCFT

Shear effect

- Modified shear force distortion relation (Vechio et al. 1986)

Flexural effect
The contribution of shear displacement is clearly greater than that of flexural displacement in the early stage but it is dominated by convenient flexural displacement at a large drift angle.

As previously explained, the curvature distribution in the analytical model is gradually formed among several monitoring sections along the member axis. In each iterative step, the internal resistance force corresponding to each curvature condition must satisfy the unique force diagram that is enforced by equilibrium. The resultant analytical curvature distributions for different drift angles are shown in Figs. 14 and 15. In those specimens whose shear span to depth ratio is 1.0, the flexural plastic hinge zone is less than 0.5 $D$ ($D =$ depth of square column section) and its length is almost 0.2 $D$ as shown in Figs. 14 and 15. Also, a flexural plastic hinge may be formed after drift angle $R = 0.8\%$ (Fig. 14) and after drift angle $R = 0.5\%$ (Fig. 15). After the formation of a flexural plastic hinge, flexural deformation gradually increases. However, when prestressing was applied through aramid fiber belts, the flexural plastic hinge zone was concentrated into the narrow zone of the column ends. Furthermore, flexural deformation was dominant in specimen ER03S-Aw65S. Thus, the analytical approach contributes to an understanding of mechanical elastoplastic behavior. For each seismic strengthening element, the
The flexural and shear strengths were calculated using AIJ simplified equations (AIJ 1999).

The fundamental seismic retrofit design concept will be carried out so that the shear strength can become larger than the flexural strength, in other words, so that flexural failure may precede shear failure. However, further investigation will be required in the near future in order to establish a design procedure for the emergency retrofit of damaged RC columns right after the occurrence of an earthquake.

6. Conclusions

1) Emergency retrofit can be applied to restore sufficient seismic performance to columns that have been damaged in an earthquake, allowing them to sustain axial force over the long term.
2) Applying pre-tension force to aramid fiber belt as the emergency retrofit contributes to closing of shear cracks, shear strengthening, axial capacity recovery and restraint of axial compressive strain through the active confinement effect.
3) The residual axial capacity of RC columns damaged in
shear failure is almost 0.2 to 0.6 of the axial compression capacity according to the damage level. However, if the emergency retrofit is applied to the damaged RC column with aramid fiber belt prestressing, concrete strength can be recovered to 60 to 100% of the cylinder strength.

4) Under a high axial force ratio of 0.4, the emergency retrofit demonstrates a sufficient reinforcing effect.

5) Fiber model analysis including the nonlinear shear force-distortion relationship is also attempted and analytical examples described in this paper. Application to flexure/shear strength evaluation for retrofitted damaged columns utilizing the constitutive model of this confined concrete will need to be further discussed in the near future.

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