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Safety assessment and strengthening method for the structural concrete with corrosion induced cracking around anchorage zones

N. Chijiwa & K. Maekawa
The University of Tokyo, Tokyo, Japan

ABSTRACT: Serious deterioration of structural safety of reinforced concrete is computationally and experimentally discussed with rapid crack propagation initiated from the corrosion cracks around anchorage zones of main reinforcement. If corrosion induced cracking occurs at the anchorage zones of structural concrete, it was to be difficult to retrofit them by means of conventional repair procedures because the load-transfer mechanism between concrete compression strut and steel tension ties is damaged. By using fracture mechanics and stress-transfer modeling across the corrosive cracks, the behavior of seriously damaged beams is reproduced. A new strengthening method is also proposed and its strengthening performance is confirmed by the analysis. Systematic parametric study for this strengthening method is performed for practical use.

1 INTRODUCTION

In the past decade, serious deteriorations of RC members caused by alkali aggregate reaction, excessive shrinkage, steel corrosion and fatigue due to repeated traffic loads have been reported (Okada et al. 1988, Rodriguez et al. 1997, Enright & Frangopol 1998, Li 2003). Thus, the need for appropriate and effective maintenance and strengthening methods is rising for longer and efficient use of concrete structures.

If RC beams which have damage only in the shear span and its anchorage zone works well, the load bearing capacity can be improved (Toongoenthong & Maekawa 2005). But when a RC beam whose anchorage zones cannot work well because of cracking or inappropriate reinforcement bar arrangement, its load bearing capacity becomes drastically smaller than sound ones (Chijiwa 2008). One of the factors of the collapse of de la Concorde Overpass in Quebec is thought to be short anchoring of corroded main reinforcement and inappropriate arrangement of shear reinforcement (Government du Quebec. 2007). It is also difficult to modify anchorage zones by strengthening at this zone because working space is limited and strengthening material cannot bear the concentrating force to this zone.

In order to recover the load bearing capacity of a beam with damaged anchorage, a new strengthening method is proposed on the basis of the concept "leave deteriorated zones but strengthening damage expected ones" for rational maintenance with high cost efficiency. In terms of material soundness, it is necessary to consider some countermeasures as a protector of steel against corrosion. As far as the structural performance is concerned, plain repair of the damaged materials is inevitable to improve the structural performance. In this study, the effect of this strengthening method is verified by experiment and FE analysis. Based on the examined FE model, some conditions are discussed to make strengthening method more rational.

2 STRENGTHENING

2.1 *Target RC beam*

This study focuses on investigating the behavior of RC beam with deterioration at anchorage zones due to corrosion. To represent this condition, a styrene board is placed right above the tensile reinforcement at each anchorage zone of the beam (Fig. 1). The length of the board is 840 mm, which is a half of the shear span. The compressive strength of the concrete is 34 MPa at 28 days, and the yield strength of the steel bars is 755MPa.

2.2 *Strengthening concept*

A new strengthening method is proposed in this study based on the following idea "leaving the damaged zones and strengthening the undamaged ones". That is, attention is now concentrated on the undamaged zone with high potential of future damage (Fig. 2). In this strengthening method, the damage is used as an underhanded way for creating new load bearing mechanism. With the target beam previously discussed, a potential damage zone is expected to occur on the tips of the artificial anchorage cracks. In terms of material soundness, it is necessary to conduct some countermeasures as a protector of steel against corrosion, but repair of the damaged materials may not be enough to recover the structural performance.

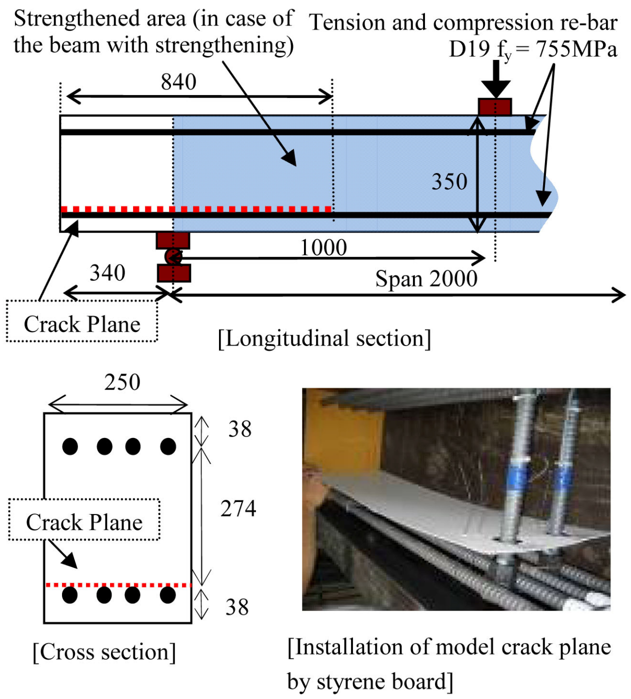

Figure 1. Detail design of the target beam.

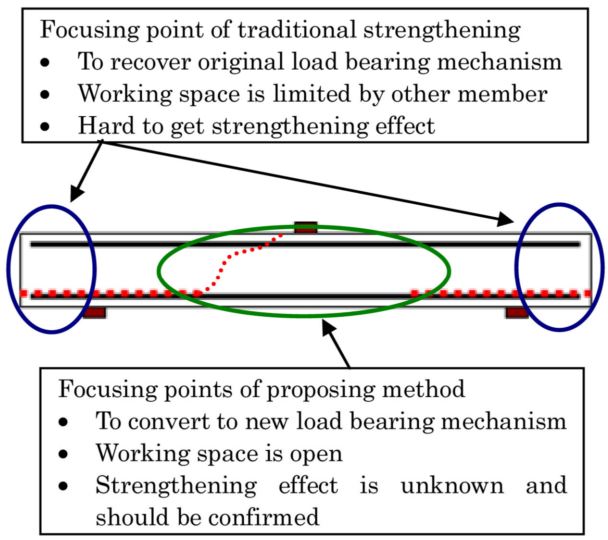

Figure 2. Concept of strengthening damage expected.

Together with the abovementioned strengthening idea, the following important issue is also considered. First, a sufficiently large strengthening area in order to avoid a sudden stiffness change and thereby result in a better stress flow. Second, highly ductile strengthening material to be compatible with large deformation of the existing damaged parts. Third, providing new stress transfer mechanism in order to substitute the lost one along the beam axis. Based on these requirements, it is proposed here to use a reinforcing sheet material called SRF (Super Reinforcement with Flexibility) (Igarashi 2002). The property of the sheet is given in Table 1. A unique feature of the sheet is that it is much softer than steel but as ductile as steel.

Table 1. Material property of the sheets.

Sheet	CFRP sheet	SRF sheet
Material	Carbon fiber	PET fiber
Young modules (GPa)	230	4.5
Rupture strength(MPa)	3400	400
Rupture strain(%)	1.48	10
Thickness of 1 layer(mm)	0.167	25
Stiffness of 1 layer (N/mm)	38.41	11.25

3 EXPERIMENT

3.1 *Strengthening area*

In the experiment, the whole shear span is wrapped with three layers of SRF (Super-ductile Reinforcement Formula) sheet. This layer number is decided based on the stiffness of one layer of CFRP (Carbon Fiber Reinforced Plastic) sheet. The influence of the layer is discussed after the strengthening effect of the proposing strengthening method is confirmed by the experiment.

3.2 *Loading condition*

Each beam specimen is tested in a simply supported condition. The width and the thickness of the supporting and the loading plates are 100 mm and 10 mm, respectively. Displacement-controlled loading condition is performed with a pace of 0.2 mm/min.

3.3 *Experimental result*

Figure 3 shows the experimental results of beam without any artificial cracks, beam with artificial cracks, and beam with artificial cracks and strengthened.

For the beam with artificial crack, a diagonal crack formed from the tip of the artificial crack when the load value reached 80 kN. The diagonal crack then penetrated to the compression side and then load value dropped to about 15 kN. Extensive slip is observed on the artificial crack. It is also observed that the amount of the slip is corresponded to the diagonal crack width.

For the beam with the artificial crack and strengthened, a steady increasing load is observed. When the load value reached 100 kN, it dropped to 80 kN. This load decrease is believed to be caused by the formation of diagonal crack and its sudden reaching to the compression bars. The sudden increase in the strain on the compression bars at this moment restates this fact. The load value then increased but it later dropped again at 105 kN as a diagonal crack formed at the other side of the beam. After that, the load value gradually increased. At this stage, two points, the tips of the anchorage crack and the intersection of diagonal crack and compression bars, became bending center, and other part of the beam acts like rigid body (Fig. 3). The beam is very ductile and even could reach the load value of 150 kN, which is similar to the capacity of the sound beam. At this load level, the load-bearing mechanism of the beam is still stable. The loading is however stopped as the deflection of the beam is beyond the measurable range of the transducers.

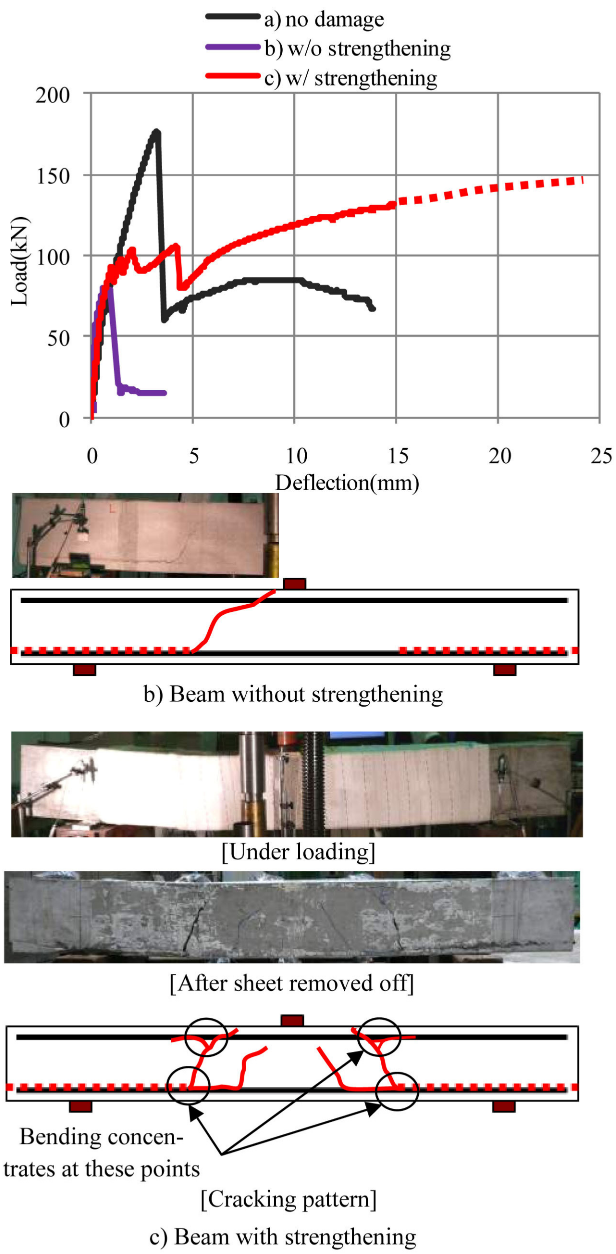

Figure 3. Comparison of the loading test results between without and with strengthened beams.

3.4 *Discussion about the strengthening effect*

For the strengthened beam, it is interesting to note that the formation of the diagonal crack is about 20 kN higher than the beam without strengthening. This fact clearly shows the role of the strengthening sheet in providing additional confinement to the crack tip.

In fact, the surface of the artificial crack is too smooth to supply enough shear force to confine crack opening in axial direction. That is why the diagonal crack from the tip of the anchorage crack reaches the compression bars just after it is formed. After the diagonal crack and compression bars intersect, bending concentrates at specific points that are mentioned in the previous section. If the beam is not strengthened by the sheet, the beam which is divided into two parts with the boundary of artificial crack and diagonal crack, and cannot carry any more loads. However, if it is strengthened, the sheet will confine crack opening in vertical direction. This confinement enlarges normal force on the artificial crack surface and friction is also enlarged. This friction becomes the axial component of the force to resist shear.

4 NUMERICAL ANALYSIS

4.1 *Analytical system*

To assess the strengthening effects, numerical analysis is conducted by a nonlinear structural analysis program for reinforced concrete called WCOMD (Maekawa et al. 2003). This analytical system is a 2-dimensional FEM nonlinear structural analysis system, which is based on a smeared multi-directional fixed crack model. This system can treat prestressing, expansion of corroded reinforcement and shrinkage of concrete caused by the change of moisture states as the cause of self-equilibrated internal stresses and cracking.

4.2 *Shear transfer model*

In the experiment, the maximum width of the diagonal crack extending from the anchorage zone is about 5mm, because the stress to confine the crack opening is small. This crack width exceeds theapplicable range of the shear transfer model originally installed in WCOMD. The original shear transfermodel (Li et al. 1989) can be applied when the normal confinement force is relatively large. But, deformation of the contact point and frictional force on that point must be considered separately when crack opens widely. Therefore, the enhanced shear transfer model (Bujadham & Maekawa 1992) is adopted and installed.

4.3 *Model for the artificial crack plane*

To model the artificial crack, a simple frictional model is employed to describe the frictional behavior on artificial crack and the loss of shear transfer when this crack is opened. Based on a supplementary small scale shear test, it is found that the apparent frictional coefficient between the concrete and the polystyrene board is about 1.1. The stiffness normal to the board is about 6.6 N/mm^2/mm, while the tangential stiffness is about 9.1 N/mm^2/mm.

4.4 *Sheet model and treatment for sheet peeling off the concrete*

The strengthening sheet is modeled as a plane element with remarkable tensile stiffness along the fiber direction (Fig. 4) and negligibly small stiffness for other directions. In the analysis, two extreme cases are adopted to represent the progress of the sheet peeled off from the concrete surface. In the first case, it is assumed that the sheet is completely unattached on the side surface of the beam. As such, different nodes are assigned to each sheet element and the element of the beam, although they are intact to each others. In the second case, a sheet is attached well only at the points which correspond to the nodes of FE analysis and other part is unattached from the beginning of loading (Fig. 5).

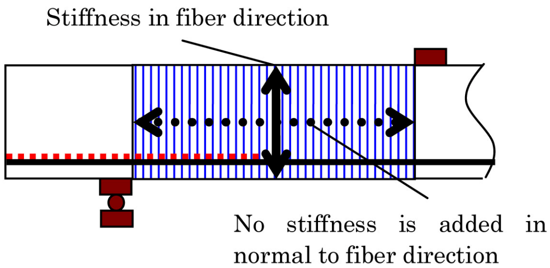

Figure 4. Sheet model.

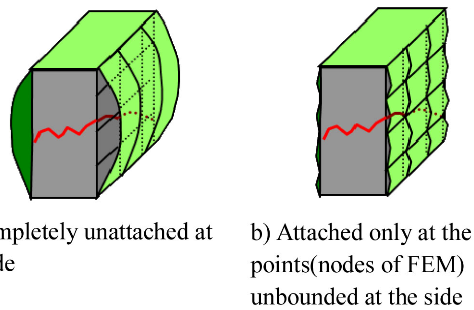

Figure 5. Bond between sheet and concrete in analysis.

4.5 *Analytical result*

Figure 6 shows comparison of experiment and analysis results of the sound beam without any artificial cracks, the beam with artificial anchorage cracks, and the beam with artificial anchorage cracks and strengthened.

For the beam with artificial anchorage crack and without strengthening sheet, the analysis can provide a general tendency of the load-deflection curve and the crack pattern. Compared to the experimental response, several differences are still observed. The difference of the initial stiffness is caused by experimental conditions. The deflection is computed by displacement at the center minus displacement at the supports, and the displacement at the support is enlarged because the soft styrene board is installed to make artificial crack plane. The difference observed in the peak load is due to the difference of frictional coefficient adopted in the analysis. The small curvature of the artificial crack in the beam affects the property of the crack modeled by a frictional model.

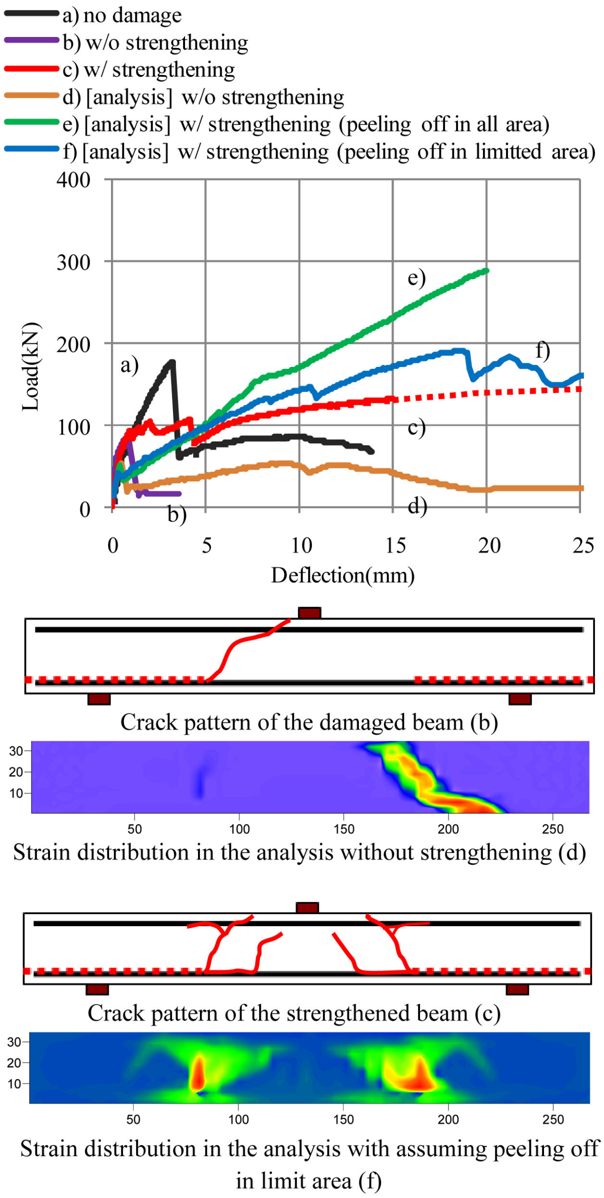

Figure 6. Comparison of analytical results of the beams with and without strengthening.

For the beam with artificial anchorage crack and with strengthening sheet, it is predicted that a diagonal crack forms at the tip of the artificial cracks at about 60kN. Due to the simplification on the condition of the strengthening sheet that is not attached as plane, the load corresponding to the formation of the diagonal crack observed from the experiment is higher than that in the analysis. After this diagonal crack formation, the beam stiffness becomes comparatively less. When the sheet is attached well only at points, the load value starts to increase again just after the diagonal crack formation. After reaching 170kN, the load becomes constant, and the load value drops more remarkably just after the diagonal crack formation. The load value then increases more rapidly than the previous case if some parts of the sheet is attached well. Finally, the ultimate capacity of the beam is predicted to be higher than that of attached well at the points.

In experiment, the area where the sheet peeled off finally is about 30 mm around the anchorage cracks and diagonal cracks. As a relatively similar peeling off area is modeled in the analysis assuming the strengthening sheet attached well only at points, a comparable load-deflection behavior is also obtained.

The analysis assuming the strengthening sheet attached well only at points can also predict the cracking behavior of the strengthened beam. The analysis can predict the opening of the tips of the anchorage cracks and the formation of other cracks around the loading points. The analysis can also reasonably re produce the observed slip occurring along the artificial crack. On the other hand, when the sheet is com pletely unattached on the side of the deflection still increases.

5 SENSITIVITY ANALYSIS FOR RATIONALIZING THE DESIGN

5.1 *Amount of strengthening*

In this section, the influence of the stiffness of the strengthening sheet on the beam behaviors is analyzed. It is assumed that the strengthening sheet does not rupture in tension and no compression bar is installed in the beam. The result shows that the strengthening effect increases in proportion with the logarithmic of the stiffness of the strengthening sheet (Fig. 7). When the stiffness of the strengthening sheet becomes comparable to that of the steel, the effect of the strengthening starts to be insignificant. It is also found that the strengthening effect depends on the shear property of the anchorage crack. The larger the shear stress can be transferred on this crack surface, the more pronounce the maximum strengthening effect is. This is because shear force which is transferred on the anchorage cracks is the source of axial force to resist external forces.

The failure pattern of the strengthened beam changes according to the stiffness of the strengthening. In case that the stiffness provided by strengthening material is too small, the beam fails due to the penetration of diagonal cracks to the compression side. This failure phenomenon is similar to the beam without any strengthening sheets. When the stiffness of the strengthening sheet is properly decided, crack is distributed and is formed not only around the tips of the anchorage crack but also around the loading point. If the stiffness of the strengthening sheet is too large, crack cannot extend through the strengthening area. The cracks now tend to extend from the tips of the artificial cracks and propagate either horizontally or vertically.

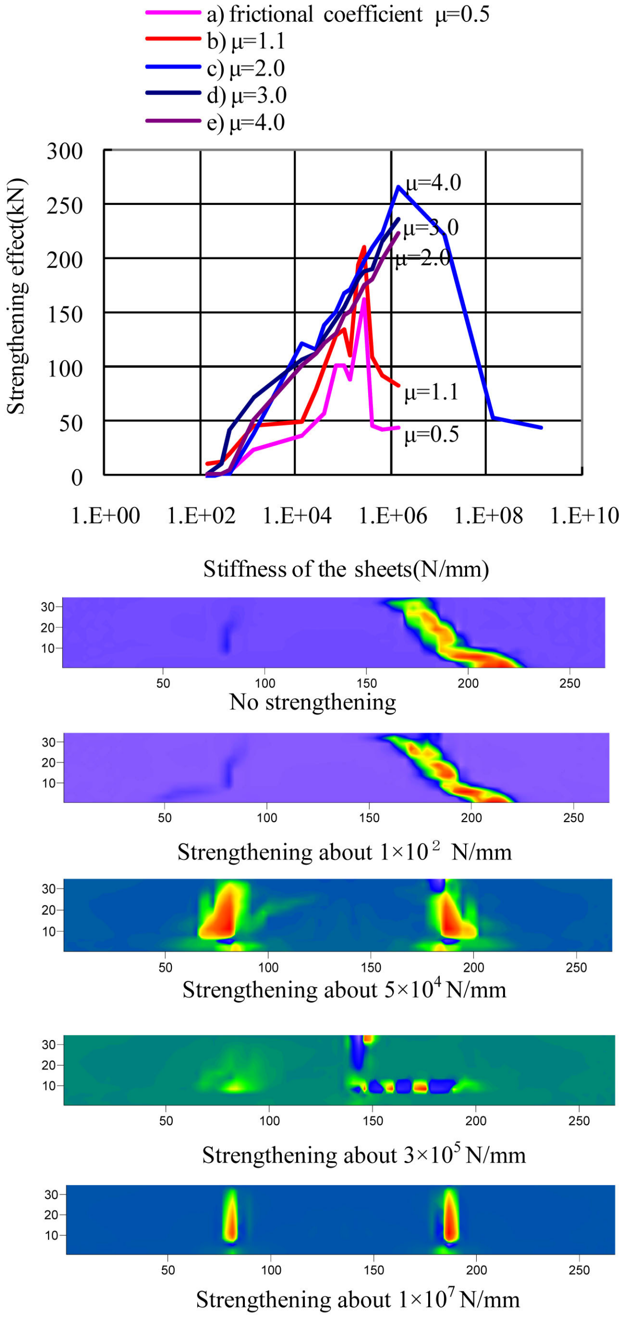

Figure 7. Shift in strain distribution at softening zone by increasing strengthening stiffness.

Apart from improving shear capacity of the beam by truss mechanism, the strengthening may also has advantageous effect in changing stress flow. When large amount of strengthening sheet are placed, new cracks will be distributed in the shear span and will not be concentrated at the tips of the artificial cracks. The optimum amount of strengthening depends on the shear property of the cracks at the anchorage zones because shear force on the cracks at the anchorage zones provide axial force to resist external force.

5.2 *Limiting the strengthening area*

The strengthening effect with limiting the strengthening area is checked by the analysis. In this analysis, compression bars are neglected for simplification, and strengthening material is 3 layers of the SRF sheet. The property of the anchorage crack is proper for the artificial crack by putting styrene board. The strengthening areas are width d (= effective depth) from the tips of the anchorage cracks to inside shear span, width d from the tips of the anchorage cracks zones to outside shear span, width 2d centering on the tips of the anchorage cracks, whole damaging area, whole sound area, and whole shear span (Fig. 8).

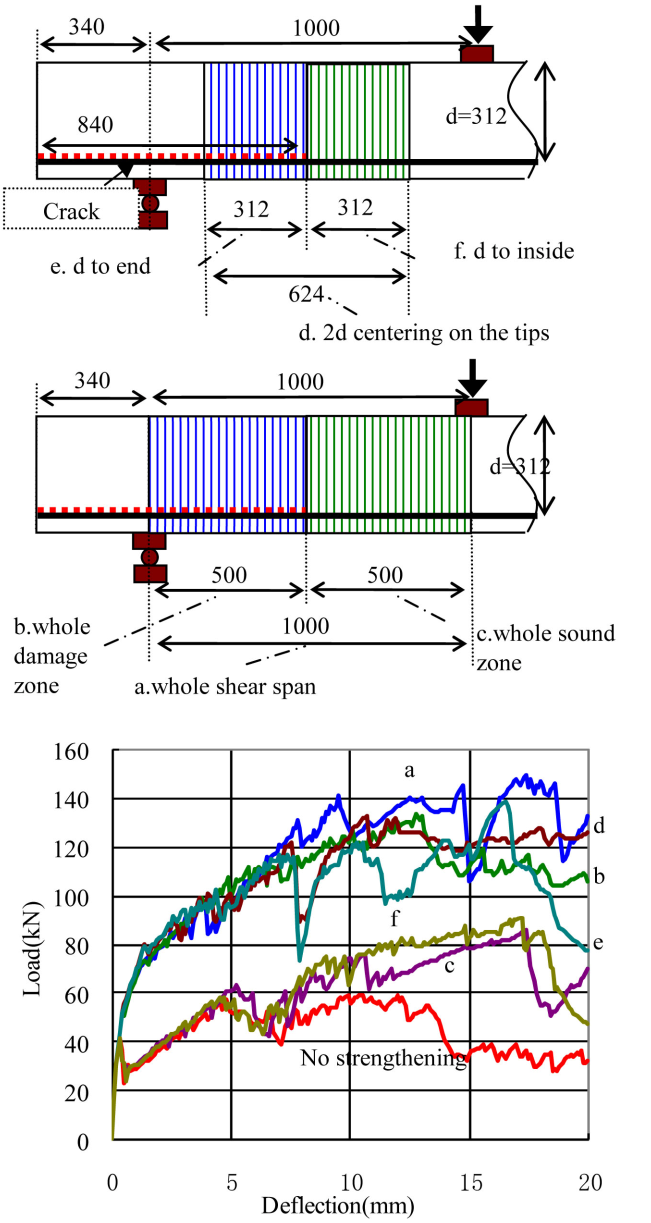

Figure 8. Analytical cases of the different strengthening and comparison of their strengthening effects.

The analytical result is also shown in Figure 8. The comparison of the strengthening effect between the strengthening at damage area and strengthening at sound area, the former one has more effect. Strengthening at damage area can inhibit the formation of the diagonal crack by diminishing the opening of the anchorage crack, and even after the crack is formed its opening is confined indirectly. On the other hand, strengthening at the sound part starts working only after crack is formed. The difference strengthening mechanism leads the difference of the strengthening effect.

When the strengthening area is limited into width d from the anchorage crack tips to inside shear span, the strengthening effect are almost as same as the case of the strengthening whole shear span. This means that it is important to confine opening of the tip of the crack in the anchorage zone.

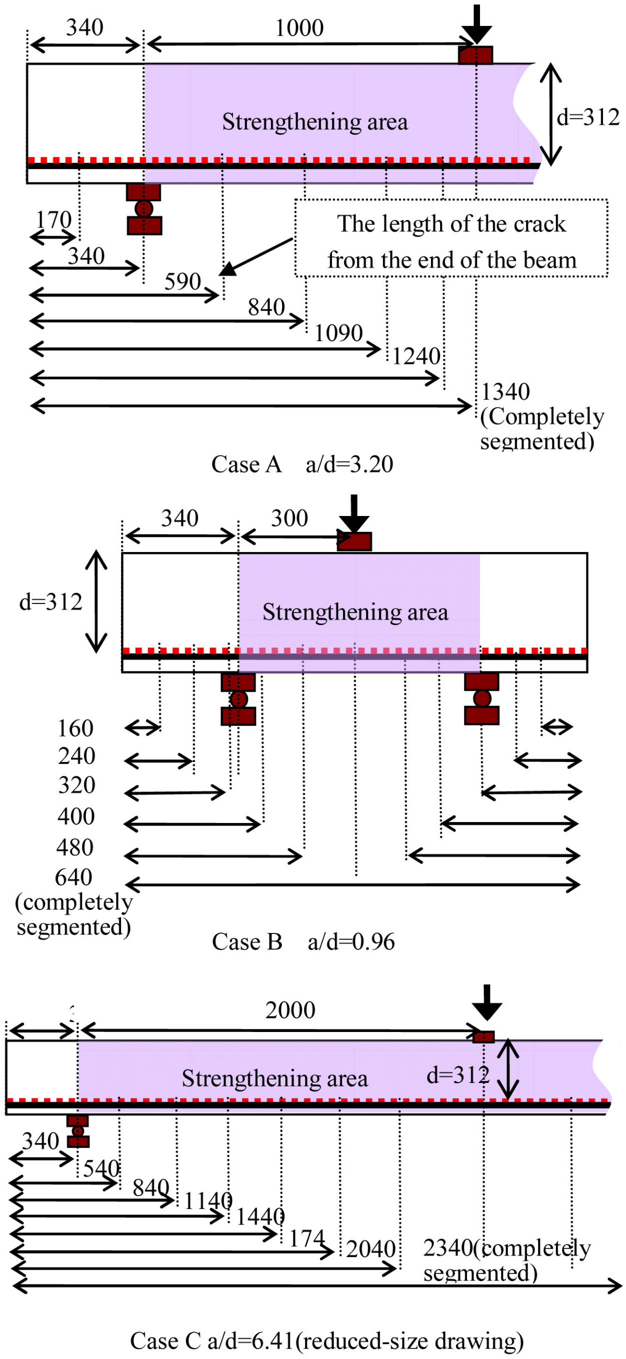

Figure 9. Combinations of the position of the tips of the.

In the case that only sound part is strengthened, there is not so much difference between the strengthening in width d and the strengthening in whole sound part. Because the diagonal cracks from the tips of the anchorage crack do not extend to the loading point but it extends to the compression side in high elevation angle, only the strengthening around the tips of the anchorage crack can work.

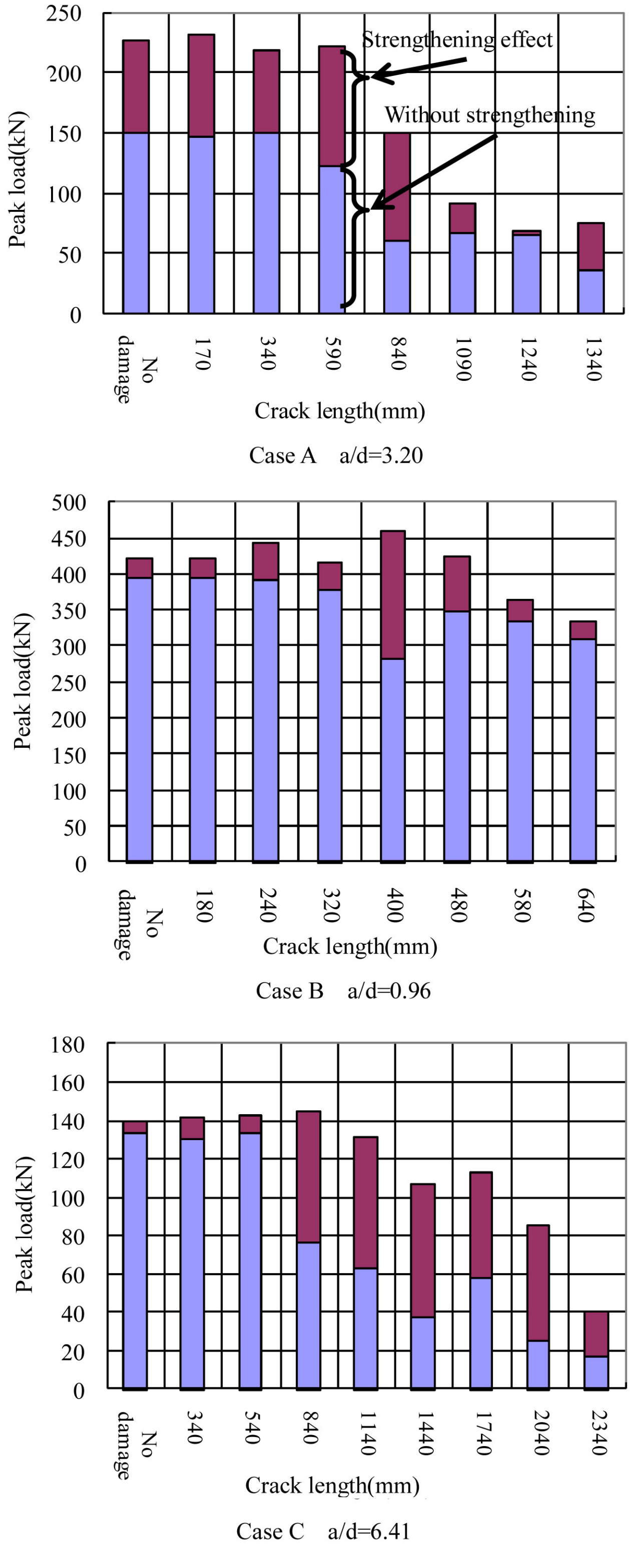

Figure 10. Shifting strengthening effect depending on the crack extending from the end of the beam.

When the sheet is wrapped around both the damage part and the sound part, the strengthening effect is more pronounce than the previous two cases by synergistic effect. This effect is due to the strengthening mechanism is different between the strengthening to the damaged part and the one to the sound part. As strengthening in width d is sufficient to get the strengthening effect in each part, so strengthening in width 2d centering on the tips of the anchorage cracks is sufficient in order to get synergistic effect.

5.3 *Strengthening effect when the crack length is changed*

The length of the anchorage crack varies from one real structure to another. In this section, the strengthening effect under some different combinations of the crack length and beam in different a/d are discussed. Assumed three beams are shown in Figure 9.

Seven different crack lengths from the beam ends are assumed: half of the anchorage zones, whole anchorage zone, 1/4 of the shear span, 1/2 of the shear span, 3/4 of the shear span, almost all span with remaining the width of the loading plate, all span. All beams are strengthened in its whole shear span. The property of the crack from the beam ends are assumed to be equivalent to the crack formed by installing styrene board.

The analytical result is shown in Figure 10.

In case that there is no strengthening, the peak load drops suddenly when the crack reaches to the point that main bars across the line between loading point and support (Fig. 11). This is because shear transfer mechanism in macro-scale is broken and the beam lost shear resistance. Only in case B, this sudden drop of the peak load cannot be observed because this beam is categorized in deep beam, and the shear force can flow to the support directly.

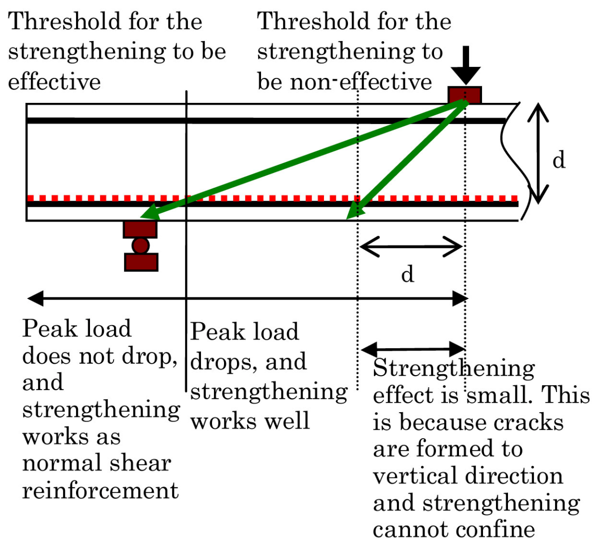

Figure 11. Classification of the strengthening mechanism.

If the crack does not reach the point that main bars across the line between loading point and support, the strengthening effect is like normal shear reinforcement. The crack extends and when it passes the point of main bars across the line between loading point and support, the strengthening works well. If the crack length is in this range, the vertical component of diagonal crack is relatively large and strengthening material can confine it well. Then sheet also supplies axial confinement by confining vertical deformation indirectly. The crack extends more and when its tip is within d (=effective depth) from the loading point, the strengthening cannot work anymore because the crack from the tips of the anchorage crack extends in vertical direction.

6 CONCLUSION

Findings in this research are listed as below.

1) The effectiveness of strengthening method on the basis of the concept as "leave deteriorated zones but strengthening sound ones" is verified by the loading test for the strengthened beam which has damages at the anchorage zone.

2) The numerical analysis with assuming strengthening sheet is attached only at the points can reproduce the characteristic features of the beam. The peeling off of the sheet have much influence to the behavior of the strengthened beam

3) It is found that there is optimum amount of strengthening. The strengthening effect increases in proportion with the logarithmic of the stiffness of the strengthening sheet. But when the stiffness of the strengthening sheet is too large, the strengthening effect starts to be insignificant. The strengthening effect is also influenced of the shear property of the crack at the anchorage zone.

4) For the monotonic loading, strengthening area can be limited in width 2d centering on the tips of the anchorage cracks. Confining the opening of the anchorage crack around its tips is important to inhibit the formation of diagonal crack and make its width small after it is formed.

5) The proposing strengthening is effective until the crack along to the main bars extends to the point which is d (= effective depth) apart from the loading point.

REFERENCES

Bujadham, B. & Maekawa, K. 1992. The universal model for stress across cracks in concrete. *Proceeding of JSCE*, No.451/V-7:277-87.

Chijiwa, N. 2008. Rational retrofitting method for reinforced concrete beam with damage at their anchorages zones. 7th International PhD Symposium in Civil Engineering, Stuttgart: chapter12 3-14.

Enright, M. P. & Frangopol, D. M. 1998. Service-life prediction of deteriorating behavior of reinforced concrete bridges. *Journal of Structural Engineering*, ASCE, 124(3): 309-317.

Government du Quebec. 2007. Commission of Inquiry into the Collapse of a Portion of the de la Concorde Overpass, http://www.cevc.gouv.qc.ca/UserFiles/File/Rapport/report_eng.pdf

Igarashi, S. 2002. SRF -a new reinforcement. *Proceedings of the JCI*, 24(2): 1273-1278.

Li, B., Maekawa, K. & Okamura, H. 1989. Contact Density Model for Stress Transfer across Cracks in Concrete. *Journal of Faculty of Engineering*, University of Tokyo(B). 40(1): 9-52.

Li, C.Q. 2003. Life-cycle modeling of corrosion performance of reinforced concrete beam damaged by corrosion of longitudinal tensile main rebar by finite element method. *Journal of Structural Engineering*, ASCE, 129(6): 753-761.

Maekawa, K., Pimanmas, P. & Okamura, H. 2003. *Nonlinear mechanics of reinforced concrete*, Spon Press: London.

Okada, K., Kobayashi, K. & Miyagawa, T. 1988. Influence of longitudinal cracking due to reinforcement corrosion on characteristics of reinforced concrete member. *ACT Structural Journal* , 85(2): 134-140.

Rodriguez, J, Ortega, L. M. & Casal, J. 1997. Load carrying capacity of concrete structures with corroded reinforcement." *Journal of construction and building materials*, ASCE, 11(4): 239-248

Toongoenthong, K. & Maekawa, K. 2005. Multi-mechanical approach to structural performance assessment of corroded RC members in shear. *Journal of Advanced Concrete Technology* . 3(1): 107-122.