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HYBRID EXPERIMENTS ON REPAIRED RC MEMBERS CONSIDERING AXIAL-FORCE EFFECTS

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SUMMARY

Some structures that were rendered nonfunctional by earthquakes could be reused after repair and strengthening of the damaged parts. Using hybrid experimental simulation by so-called HYLSEER (Hybrid Loading System of Earthquake Response), we investigated seismic behavior and energy-absorbing capacity of repaired reinforced concrete (RC) members. Two repair methods were used, and the behavior of the repaired specimens was compared with previously tested original specimens. Results show that energy-absorbing capacity of repaired specimens could be restored to that of the unrepaired originals when suitable repair methods were used.

INTRODUCTION

The use of epoxy resin in repairing RC structures has been found to be applicable and effective. It is important to determine how such repaired structures will respond during future earthquakes. However, seismic behavior of repaired RC structure is difficult to evaluate by purely analytical means. Hybrid experiments provide very effective and powerful techniques to investigate the earthquake responses of such complicated materials as RC members or soils (Refs. 1, 2, 3).

A description of HYLSEER (Hybrid Loading System of Earthquake Response) used to analyze repaired RC members under varying bending loads and constant axial force, and an analysis of hysteretic energy-absorbing process for these members during earthquakes are given. Deterioration process of energy-absorbing capability also is estimated analytically.

HYBRID LOADING SYSTEM OF EARTHQUAKE RESPONSE (HYLSEER)

Eight specimens were used, all having the dimensions 100x150x1900mm (Fig. 1) and a distance between supports of 1500mm. They were doubly reinforced by D10 bars (steel ratio 1.1%). Concrete was confined by providing stirrups (diameter 6mm) every 70mm. The schedule of loadings for the entire experiment is shown in Table 1.

A hybrid loading system of earthquake response, called HYLSEER (Fig. 2) was used to test specimens modeled as a single-degree-of-freedom system. A microcomputer was used to solve the equation of motion in order to obtain the deformation at the next time step using the step-by-step integration.

$$m\ddot{x}(t) + c\dot{x}(t) + F(x(t)) = -m\ddot{z}(t)$$

Table 1 Loading histories. (E, El Centro NS ; H, Hachinohe NS ; digits 100 - 300, max. acc. in gal ; EPOXY, epoxy resin grouting method ; PLATE, steel plate covering method.)

No.	initial loading	loading without repair	repair method	loading after repair	ultimate loading
1	100 H	250 E	PLATE	100 H	250 E
2	150 H	200 E	EPOXY	150 H	
3	250 H		EPOXY	250 H	
4	300 H		EPOXY	300 H	
5	150 E	300 E	PLATE	150 E	300 E
6	200 E		EPOXY	200 E	
7	250 E		EPOXY	250 E	
8	300 E		EPOXY	300 E	

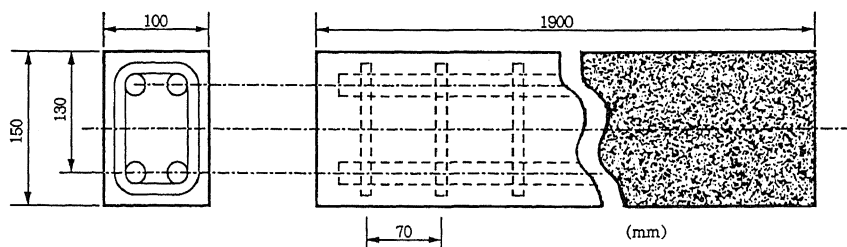


Fig. 1 Specimen dimensions.

in which, m is the mass; $x(t)$ the relative displacement at time t ; c the damping constant; $F(x(t))$ the hysteretic restoring force at time t ; \ddot{z} the ground acceleration; and a dot (·) indicates the time derivative.

In solving the equation of motion, the hysteretic restoring force could be estimated directly from the on-line experiment step-by-step. The actuator (Fig. 2, No. 2) controls the midspan of the single supported specimen (Fig. 2, No. 4) using the computed displacement $x(t)$ sent through a DA (digital to analog) converter (Fig. 2, No. 8). In return, the computer (Fig. 2, No. 9) gets the measured restoring force $F(x(t))$ from the actuator received through an AD (analog to digital) converter.

Using the axial force generating mechanism, in which a constant axial force is sustained by high-pressure oil built up by pressurizing air, constant axial force $N=4.0\text{tonf}$ (39kN) was applied.

The NS-components of the El Centro record (1940 Imperial Valley earthquake, U.S.A.) and the Hachinohe record (1968 Tokachi-Oki earthquake, Japan) were the input earthquake excitations used. 30 seconds of these records were used. They were set to have the maximum values in the range of 100 to 300 gal (cm/sec^2).

The two repair methods used are

(a) The Epoxy Resin Grouting Method: First, mixed epoxy resin and sand were put on the heavily damaged parts, then, setting pipes were attached to the cracks, and sealed with epoxy bond. After that, epoxy resin was grouted into the cracks using the BICS (Balloon Injector for Concrete Structures, Ref. 4) at a low pressure of about $3\text{kgf}/\text{cm}^2$ ($0.3\text{MN}/\text{m}^2$).

(b) The Steel Plate Covering Method: The damaged segment was filled with mixture of epoxy and sand, after which steel plates were bonded to the damaged part with epoxy resin. Epoxy resin then was grouted into the cracks by the same technique as method (a). The thickness of the steel plate used was computed as having the same moment of inertia as the original reinforcing bars; that is, the moment of inertia of the specimen was restored to the original value by the steel plates, assuming that the damaged reinforcing bars were totally incapacitated.

In a previous study (Ref. 5), we found that specimens with minor cracks could be adequately repaired with epoxy resin. In the study reported here, strong acceleration also was applied to unrepaired specimens to obtain heavily damaged specimens and to observe the destruction process (specimens 1, 2 and 5).

The details of the experiments are given in Ref. 6.

HYSTERETIC ENERGY DISSIPATION

Energy-absorbing capability should be taken into account while investigating damage to specimens. The energy imparted by earthquake motion is dissipated as the kinetic energy, the damping energy and the hysteretic energy. The absorbed hysteretic energy, W_H , is a major factor in the structural damage produced by cyclic loadings. It is calculated as being the area enclosed by the hysteresis loops. During an earthquake, capability of absorbing the hysteretic energy deteriorates as the shape of hysteresis loop changes. In this chapter, the deterioration process of this capability is discussed.

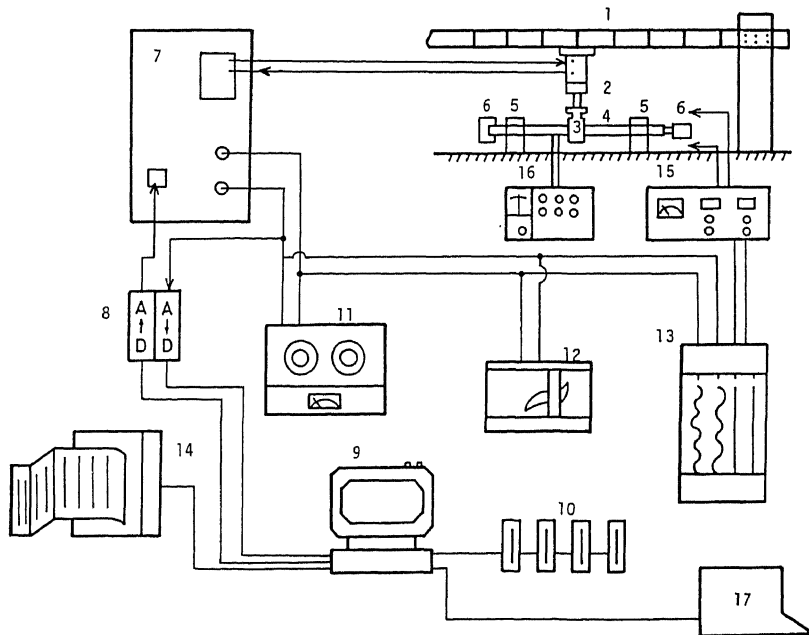


Fig. 2 HYLSEER (Hybrid Loading System of Earthquake Response) diagram.
 1. Frame 2. Actuator 3. Loading Frame 4. Specimen 5. Simple Support
 6. Axial Force System 7. Central Controller 8. AD-DA Converter
 9. Microcomputer 10. Floppy Disk 11. Data Recorder 12. X-Y Recorder
 13. Pen Recorder 14. Line Printer 15. Dynamic Strain Gage
 16. Static Strain Gage 17. Kyoto Univ. Data Processing Center

We defined the index for the deterioration process of energy-absorbing capability as follows:

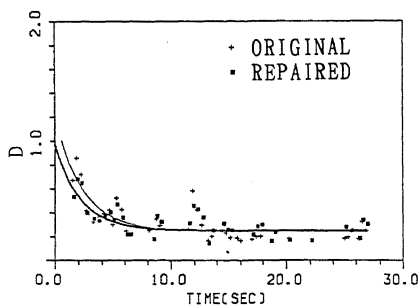
$$D(i) = \frac{W_H(i)}{W_H(0)}$$

where $D(i)$ is the index at the i -th loop, $W_H(i)$ the hysteretic energy dissipated at the i -th loop, $W_H(0)$ the hysteretic energy that might be dissipated if the same deformation were applied as the first cycle of loading corresponding to the maximum displacement at the i -th loop; i.e. the capability of absorbing the hysteretic energy was supposed not to deteriorate. The force-deformation relation of static loading test was used to evaluate $W_H(0)$. As the unloading characteristics can not be evaluated from the static tests, we assumed unloading stiffness of Takeda's hysteresis rule.

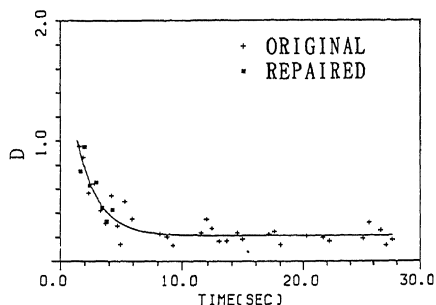
$$\begin{cases} K = K_0 & (0 < \mu \leq 1) \\ K = K_0/\sqrt{\mu} & (\mu > 1) \end{cases}$$

where K_0 is the initial unloading stiffness, and μ the maximum ductility of each cycle of hysteresis loop.

Some time histories of D index are shown in Fig. 3. The lines in these figures are the regression curves using exponential function. It is seen that the difference of maximum input acceleration had little effect on time histories of D index. D index becomes less than 1 when the inelastic response begins, and goes down to 0.2-0.4. D index shows small change in the last 10 seconds, where the response is small.

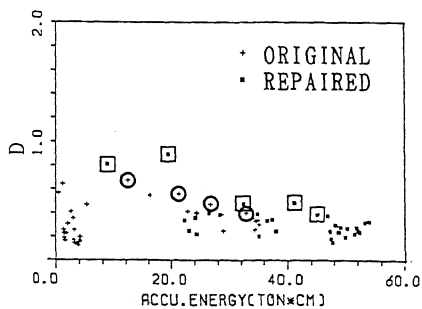


(a) Specimen 6 (El Centro 200gal)

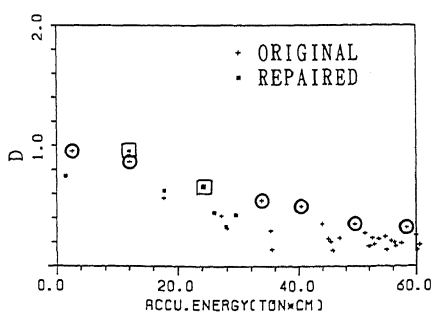


(b) Specimen 8 (El Centro 300gal)

Fig. 3 Examples of D index - time histories.



(a) Specimen 1 (Hachinohe 150gal)



(b) Specimen 8 (El Centro 300gal)

Fig. 4 Relationship between D index and accumulated hysteretic energy.

Fig. 4 shows the relation of D index and accumulated hysteretic energy. The points surrounded by circles or rectangles in these figures are D indices at large deformation. Circles are for the original specimens, and rectangles for the repaired ones. D index checked by circles or rectangles decrease almost linearly as the accumulated energy increase. This tendency is clear especially in the case of strong input acceleration (Fig. 4-b).

The difference of deterioration process between repair methods are as follows. After the specimen was repaired using the epoxy resin grouting method, deterioration of energy-absorbing capability becomes heavier than or as same as before (Fig. 4-b). If it was repaired using the steel plate covering method, deterioration of energy-absorbing capability is less than the original specimen (Fig. 4-a). From this point of view, the steel plate covering method is appreciated.

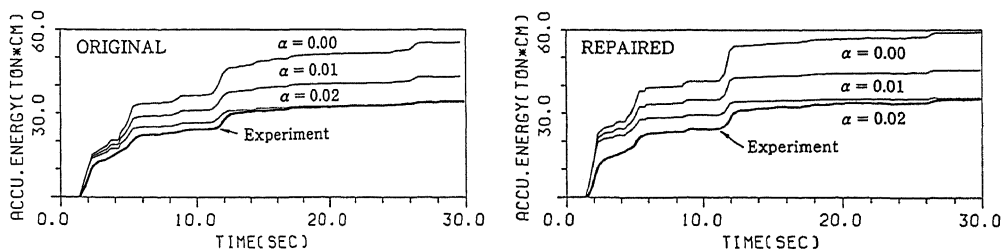
ESTIMATION OF ENERGY ABSORBING CAPABILITY

In the previous chapter, we showed capability of absorbing hysteretic energy deteriorates linearly by large deformation. We tried to estimate analytically the amount of absorbed hysteretic energy at the i -th cycle of hysteresis loops; $W_H(i)$.

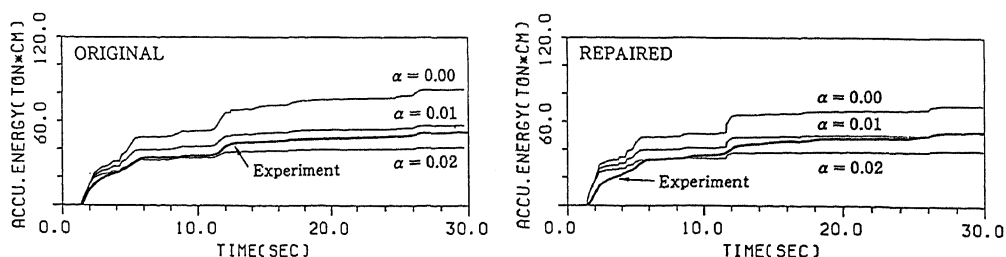
$$W_H(i) = W_H(0) (1 - \alpha \cdot \Sigma W_H(i-1))$$

where α is the coefficient for deterioration of capability for absorbing hysteretic energy. We used 3 values for α ; $\alpha=0, 0.01$ and 0.02 . $\alpha=0$ means the capability of absorbing it does not deteriorate at all.

The absorbed hysteretic energy calculated by the method above using displacement response of the hybrid test was compared with the real absorbed hysteretic energy during the hybrid test. Fig. 5 shows that calculated values are good estimation of W_H for the original specimens, as well as the repaired ones. The α coefficient is in the range of 0.01 to 0.02. However, this method is appreciated for the case of large response. Because when the input excitation is not strong, the hysteretic energy was over-estimated.



(a) Specimen 6 (El Centro 200gal. Repaired by epoxy resin grouting method.)



(b) Specimen 7 (El Centro 250gal. Repaired by epoxy resin grouting method.)

Fig. 5 Tested and calculated process of absorbing the hysteretic energy.

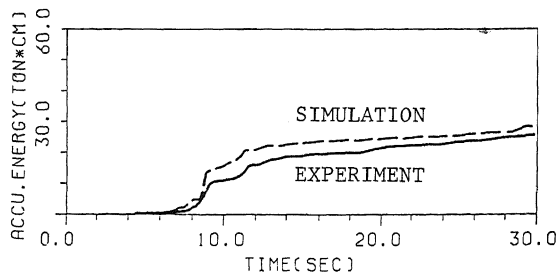
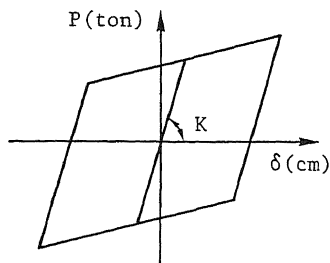


Fig. 6 Conventional bi-linear model.

Fig. 7 Comparison between experiment and simulation of absorbed hysteretic energy. (Specimen 3)

As the displacement response can be estimated correctly by using simple models, this method is applicable widely. For example, we used bi-linear hysteresis rule (Fig. 6) to predict absorbed hysteretic energy. Fig. 7 shows comparison between experimental results (a solid line) and simulation (a broken line) for repaired specimen 3. The broken line can be good estimation for the solid line.

CONCLUSIONS

The hysteretic energy-absorbing processes of repaired RC members under constant axial force were studied, with the main results being that

1. deterioration process of capability for absorbing hysteretic energy can be estimated using the force-deformation relation of statically loading test and unloading characteristics of the analytical model.
2. hysteretic energy-absorbing processes of specimens repaired by the epoxy resin grouting methods showed heavier deterioration than those of original ones; whereas, the processes of specimens repaired by the steel plate covering methods showed less deterioration than those of unrepaired originals.
3. the accumulated absorbing hysteretic energy was estimated correctly by using the linear deterioration assumption for hysteretic energy-absorbing process. The constant that represents deterioration process was 0.01 to 0.02.

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