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# Reinforced concrete filled steel shell able to endure any large earthquake

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## *Abstract*

In the past great earthquakes in the world, many reinforced concrete (RC) structures have suddenly collapsed or been severely damaged by the large shear strain of vertical or horizontal impact waves. Since these breaking faces start from the central area of the cross section in the structures where the shear stress is the maximum, the failures of the RC structures occur suddenly while the shear plane reaches the surface of the structure where the shear stress is the minimum. The sudden collapse of RC structure must be prevented to keep the lives of people inside or on the structure. To prevent such collapse and damage, it is necessary to reinforce the central portion of the cross section in the structures. By this reinforcement the structures can keep an excellent toughness, a continuous strength curve and its shape, avoiding sudden collapse.

To endure the excessive seismic force over the design load, a reinforced concrete filled tube (RCFT) and a reinforced concrete filled steel shell (RCFS: the reinforced concrete covered with steel plates) are applicable. The load-displacement curve shows that RCFT maintains the almost maximum vertical load, consisting of the maximum strengths of steel shell and RC each and it can endure a few times of the maximum load with the large displacement, following the equal-energy principle. It is very important to keep a good toughness absorbing high stress with ductility for prevention of structural damage against the strong impact waves.

RCFT also has a good toughness and a preferable performance for bending moment comparing with concrete filled shell (CFT). The flexural capacity of RCFT is 1.5 ~ 2 times of the steel tube with a small deflection curvature whose fissure of RC inside is almost invisible. RCFT has relatively stable values of dumping constants over the wide range of displacement, to attenuate its shaking during a great earthquake. Thus, RCFT and RCFS are one of the most suitable construction members for the seismic design to any great earthquake.

*Key Words: RCFS; CFT, impact wave; shear strength, toughness*

## 1. Collapse of RC and steel structures 〔1〕

In the past great or large earthquakes in the world, many reinforced concrete (RC) structures have suddenly collapsed or been severely damaged by the large shear strain of vertical or horizontal impact waves. In the 1995 Southern Hyogo Prefecture Earthquake, many reinforced concrete structures on the diluvium ground were collapsed in state of shear failure. Fig.1 is a collapsed pier of viaduct with straight shear plane. Fig.2 is some collapsed piers of viaduct with conjugated shear planes. In case of building, a few buildings on the firm ground demolished intermediate stair because of collapse of columns. Fig.3 shows an office building lost the 4$^{th}$ floor. Fig.4 is an aerial view of building of Kobe City Hall broken the 6$^{th}$ floor. However, the pancake collapses as shown in the 1985 Mexico City earthquake (Fig.5) were not discovered.

The evidence able to explain the mechanism of these collapses was observed in the damaged building of Hachinohe City Hall (Fig.6) in the 1994 Far-Off Sanriku earthquake. Though the building had not collapsed, it received the apparent conjugated shear cracks on the middle columns (red circle) and the minute straight crack on the edge columns of 1$^{st}$ stair. It is supposed that if the acceleration of seismic waves were larger, the 1st stair collapsed similarly as those in Kobe.

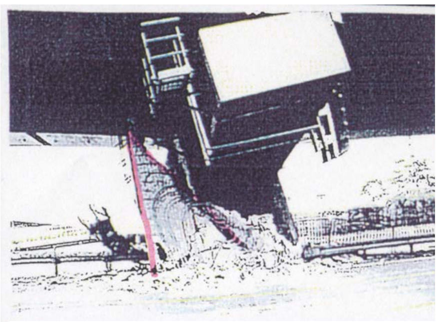


Fig.1 Collapsed pier of viaduct with straight shear plane

Fig.2 Collapsed piers of viaduct with conjugated shear planes

Fig.3 Collapse of 4th floor of a office building

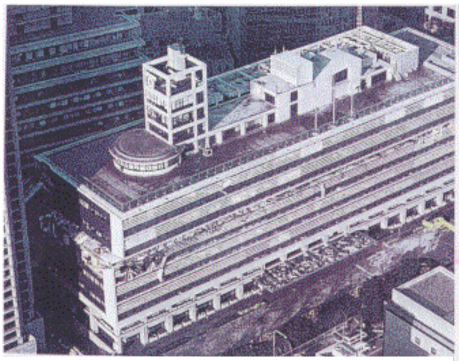


Fig.4 Collapse of 6th floor of Kobe City Hall

Fig.5 Apartment Complex Pino Suárez, in the wake of the 1985 Mexico City earthquake

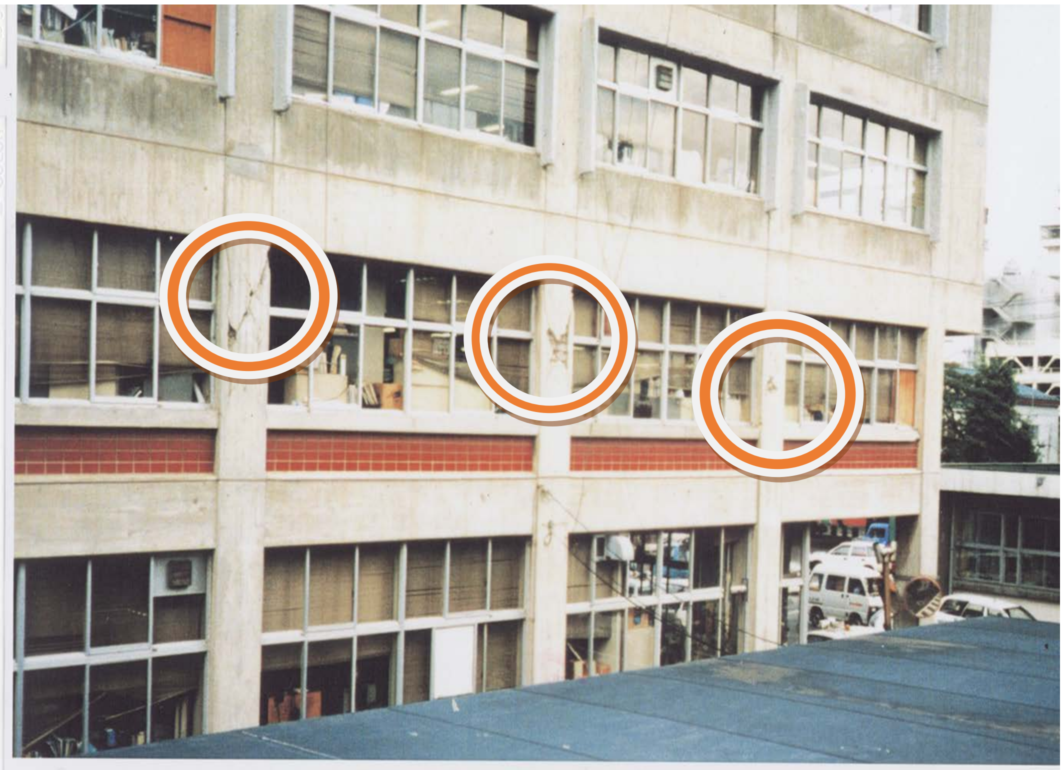


Fig.6 Conjugated cracks on middle columns of building of Hachinohe City Hall



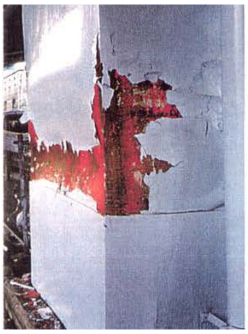


Fig.7 Buckling on steel pier


Fig.8 Buckling collapse of steel pier

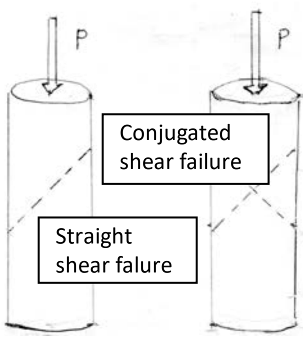


Fig.9 Shear failures of RC

In Kobe, several buckled steel piers of viaduct were found as shown in Fig.7 and Fig.8. From a series of phenomena, the collapses of RC structures and steel structures are considered depending on the vertical waves in the earthquake. Fig.9 shows two types of shear failure of RC test pieces, as born on the RC structures. However, the values of observed seismic records is not always large to collapse these structures.

The similar damage of bridges on the rigid foundation had been observed in Japan. Fig.10 is the damaged pier of Yuriage Bridge in Miyagi prefecture in the 1988 Off-Miyagi Earthquake. The RC pier of

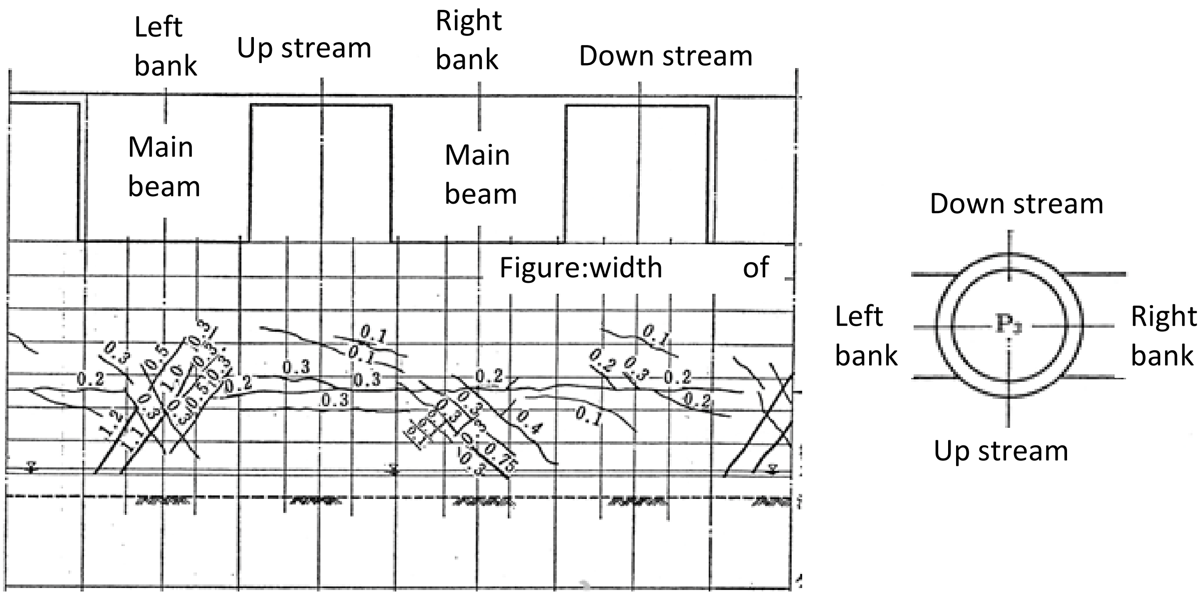


Fig.10 Shear cracks and tension cracks on cylindrical RC pier in the Off-Miyagi Earthquake

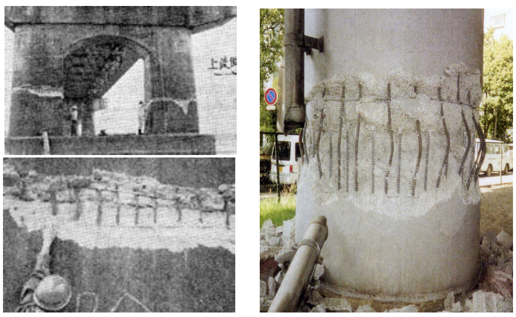


Fig.11 Tension cracks of RC piers


Fig.12 Shear failure of RC pier in the 1982 Off-Urakawa Earthquake

prestressed concrete bridge took a shape of cylinder to reduce the influence of vertical load to the caisson foundation. Many conjugated shear cracks and tension cracks generated around two main piers. On other piers of side bridges a few shear cracks were observed. The whole bridge itself could escape collapse and reinforce the structure. In the 1988 Off-Miyagi Earthquake, many RC piers of bridges on caisson foundation were received damage of shear failure and tension crack. Fig.11 displays the RC piers damaged by the vertical tension in the 1988 Off-Miyagi Earthquake and the 1995 Southern Hyogo Prefecture Earthquake. Fig.12 shows the shear failure of RC pier of Shizunai Bridge in Hokkaido in the 1982 Off-Urakawa Earthquake. The pier also was constructed on a caisson foundation.

## 2. Seismic waves observed 〔2〕

Fig.13 is the record of the acceleration waves of the 1995 Southern Hyogo Prefecture Earthquake at Kobe Marine Meteorological Office and shows their response spectrums. The office building is placed on the diluvium stratum with a deep foundation, few km apart from the seriously damaged area. The accelerations of vertical wave are smaller than those of horizontal wave regardless of the vertical collapses of structures. The reason not to connect the vertical waves with the collapses is considered because the existing seismographs can not measure the impact waves with higher frequency than 50 Hz. The impact waves with very high frequency rarely have large acceleration exceeding the design load.

Fig,14 shows the record of acceleration by a high-performance seismograph at the station west of Ichinoseki near the epicenter in the 2008 Iwate-Miyagi Inland Earthquake. The vertical waves include very high acceleration of 3886 gal. Their response spectra are given in Fig.15. They indicate that the maximum value of vertical waves reached at about 9000 gal for those of horizontal waves about 5000 gal, and the rising response curve is cut at 50 Hz. By this earthquake many hillside collapses and debris flows were occurred. The similar phenomenon was observed in the 2018 Hokkaido Iburi East Earthquake. The maximum acceleration of vertical waves was 1591 gal at the station apart 15 km from the epicenter and the response spectrum of acceleration was about 4000 gal at 50 Hz. The innumerable hillside collapses generated between the epicenter.

For the resolution of this problem a new type of seismograph able to record the seismic waves with 500 Hz was experimentally made under cooperation with Dr.T.Sakai. The main components and its schema are shown in Fig,16 and Fig.17. Though two seismographs had installed at different places, they could catch

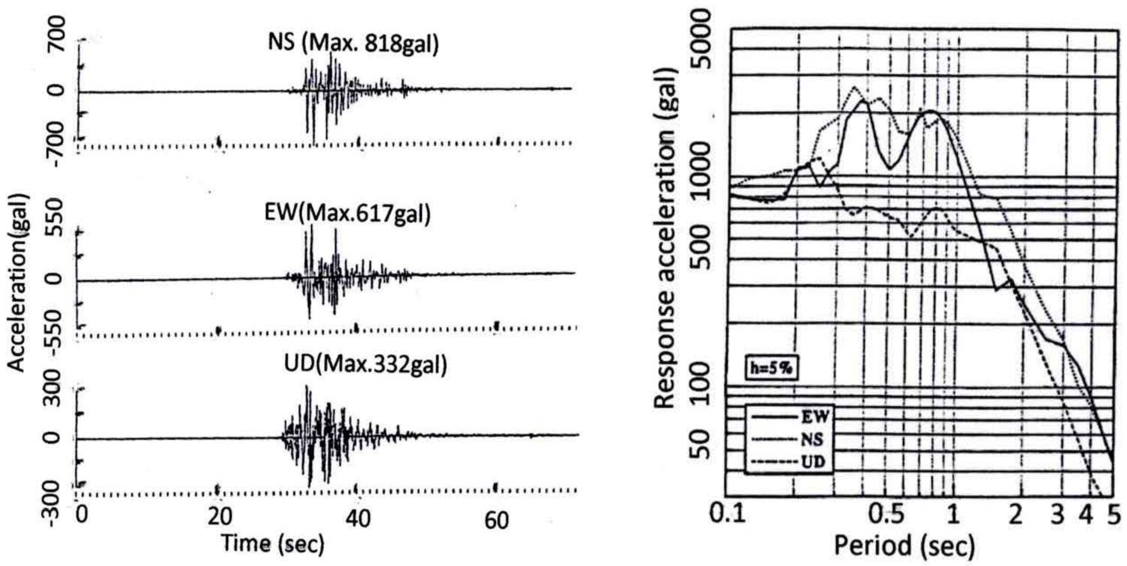



Fig.13 Acceleration waves and their response spectrums of the 1995 Southern Hyogo Prefecture Earthquake at Kobe Marine Meteorological Office



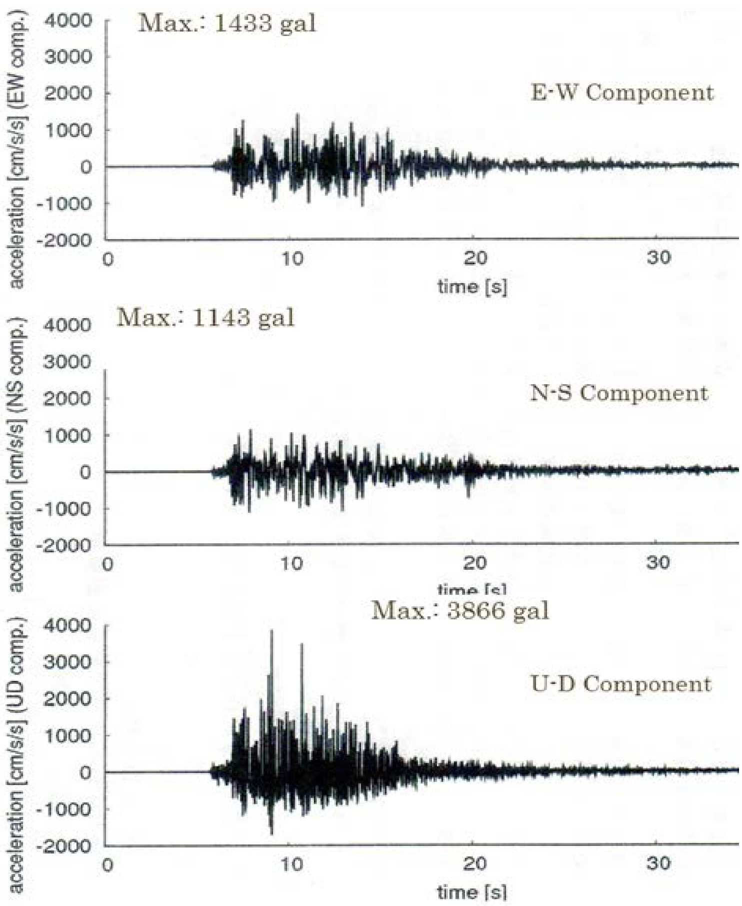



Fig.14 Seismic waves recorded in the Iwate-Miyagi Nairiku Earthquake in 2006

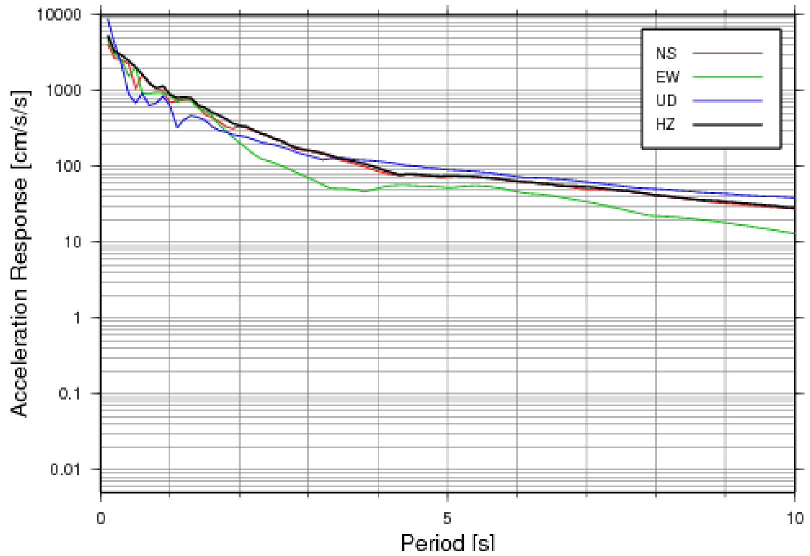



Fig.15 Responce spectra of acceleration in Fig.11



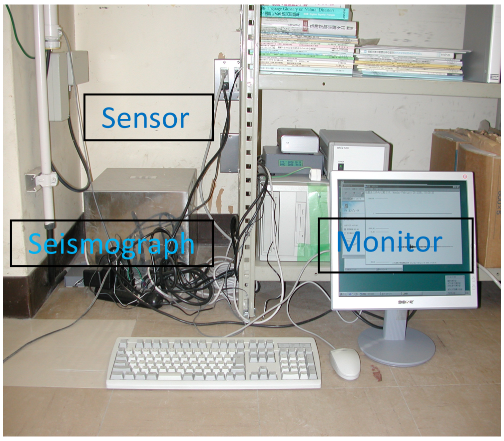



Fig.16 Composition of wide range seismograph

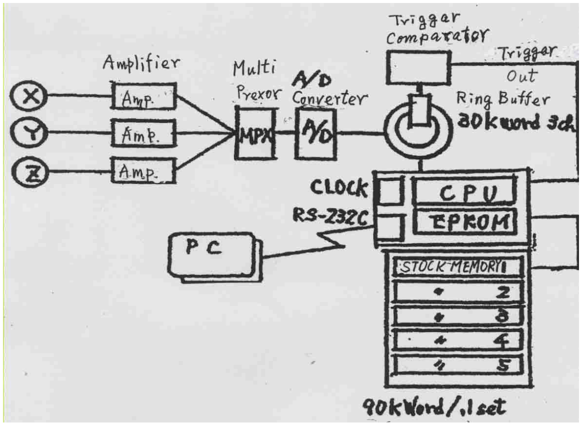



Fig.17 Schema of wide range seismograph

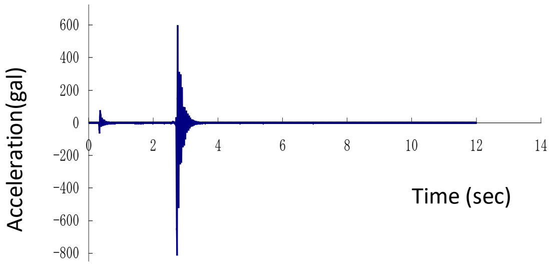



Fig.19 Impact waves of falling weight measured with normal seismograph

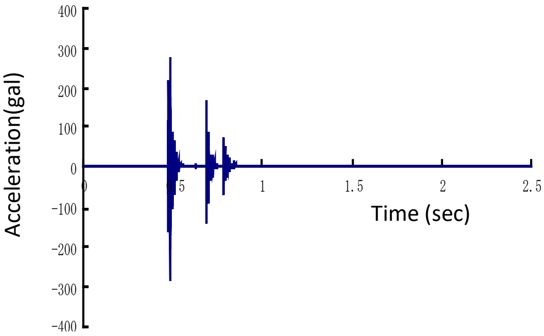



Fig.18 Impact waves of falling weight measured with wide range seismograph

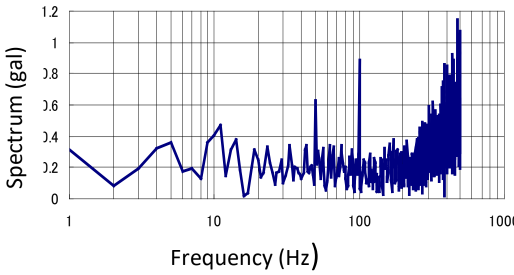



Fig.20 Response spectrum of impact waves from wide range seismograph

none of large earthquake. Then, to investigate the new seismograph a series of falling weight tests were performed on RC floor together with a normal seismograph fixed on the wall. The weight of iron block with 10 kg fell from a height of 30 cm. the results of two seismograph are shown in Fig.18 and Fig.19.

Fig.18 expresses waves of bound and Fig.19 shows the waves summed up. Fig.20 is the response spectrum of impact waves measured with the wide range seismograph. These figures demonstrate the accurate performance of the new seismograph and the highly responded waves of more than 500 Hz. Furthermore, they suggest the necessity of development of the more accurate seismograph able to measure the waves with higher frequency for investigation of the above-mentioned collapse.

## 3. Seismic design for RC structure 〔3〕

Many RC structures collapsed or received damage of shear crack under the large earthquakes. The cause of damage is mainly considered depending on the vertical impact waves as mentioned above. The vertical load of impact waves acts as compression load to the structures. By compression force the shear stress ( τ ) generates and changes in a column (Fig.21). Fig.22 shows the shape of distribution of shear stress in a column calculated with 3-dimensional FEM analysis. Since the intensity of shear stress increases at the center along the axis, the shear failure starts from the center of cross section and looks as a brittle failure when shear plane extends to the edge. To prevent such failure, it is recommended that the shear reinforcements (Fig.23) shall penetrate the center of cross section in regular intervals.

However, since the reinforcing bar arrangement (inner ties) to penetrate the cross section is troublesome work at site, it is recommendable to insert the prefabricated reinforcement cage (Fig.24, Fig.25) in the center of section after arrangement of the main reinforcement. Fig.26 and Fig.27 are load-displacement curves of compression tests for the test pieces with a conventional and a double reinforcement respectively.

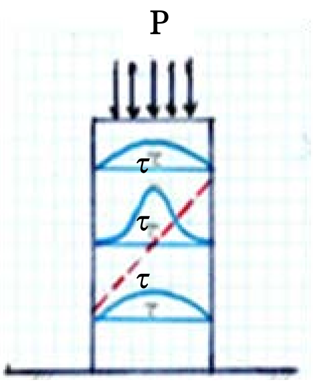
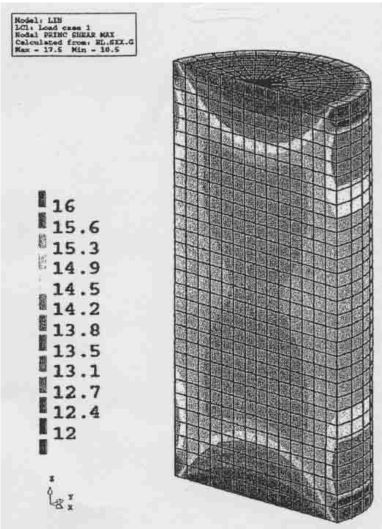
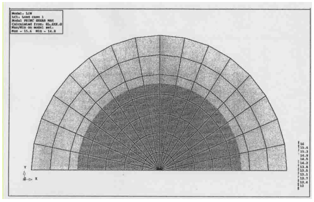
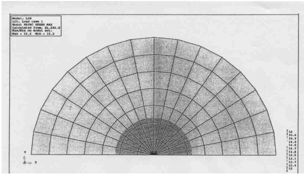



Fig. 21 Shear failure plane by compression



Shear stress of column at 1/4 of height



Shear stress of column at half of height

Fig..22 Distribution of shear stress in a column calculated with 3-dimensional FEM analysis

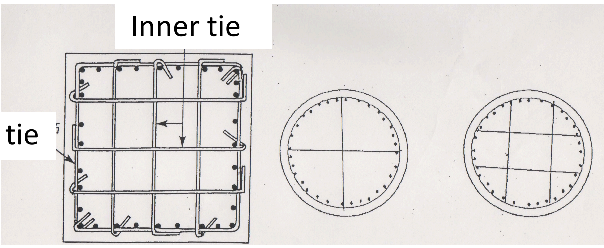



Fig.23 Examples of shear reinforcements (inner tie)

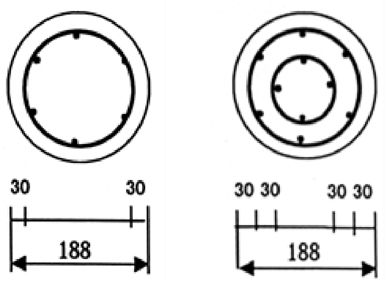



Fig.24 Examples of a conventional and a double reinforcement cage

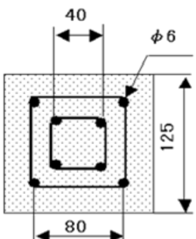



Fig.25 Square column with double reinforcement



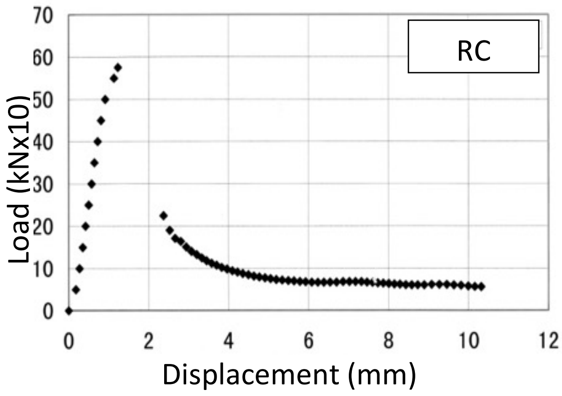



Fig.26 Load-displacement curve of compression test of common RC column with a single reinforcement cage

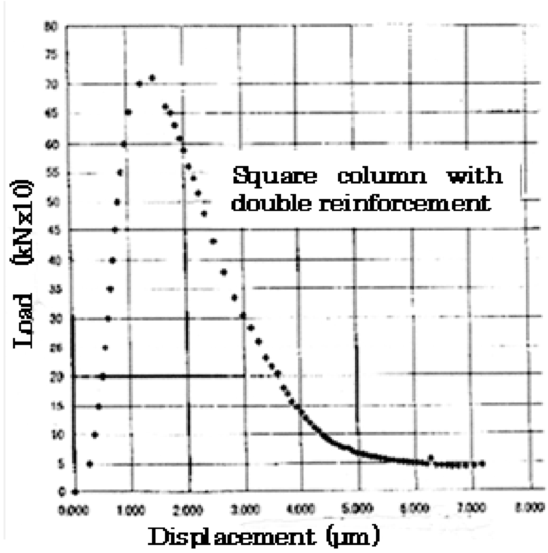



Fig.27 Load-Displacement curve of test of square RC column with a double reinforcement cage

Fig.28. Test pieces of column broken with double reinforcement cage and inner cages of specimen after compression test

In case of the conventional reinforcing bar arrangement, the load-displacement curve becomes discontinuous after the maximum load. It means the sudden collapse of RC structure. On other hand, in case of the double reinforcement cage the load-displacement curve is continuous till large displacement and the test piece maintains a level of residual strength. It means possibility to keep the shape of structure and to protect lives and assets even if destroyed in large earthquake.

Fig.28 shows the results of compression test of RC test pieces with double reinforcement cage. The test piece kept its shape and the core of inner cage remained with bend under the shear force. The reason of the continuity of load-displacement curve and the residual strength able to support dead load is based on this core of inner cage. Since the shear strain at the peripheral area of the test piece in Fig.24 is almost zero, the reinforcements of outer circle are not efficient for the shear stress. The reinforcement at the center of cross section is essential to prevent collapse of structure. To prevent the shear failure of RC structures these relations should be emphasized in various Technical Standards. For the double reinforcement instead of the inner ties, it is easy to insert a prefabricated small cage inside of the outer cage using a crane.

## 4. Reinforced concrete filled tube (RCFT), reinforced concrete filled shell (RCFS)

The maximum strength of RC test piece with a double reinforcement is almost same to that with a conventional reinforcement. So that the structures react an extraordinary load or too sharp impact waves and keep safety and function, a reinforced concrete filled steel tube (RCFT) and a reinforced concrete filled steel shell (RCFS) are appropriate to absorb such excessive forces over the design loads. RCFT (Fig.29) is a structural member of reinforced concrete inside of CFT (concrete filled tube) with the inner cage. RCFS (Fig.30) also is a structural member of reinforced concrete inside of the steel shell with the inner cage and the shear connectors. The inner cage has a role to protect concrete inside of steel plate from the shear strain and the shear connectors unify the steel plate and the concrete inside.

To investigate the performances of RCFT for the excessive forces over the design loads, a series of compression and bending tests were conducted (Fig.31). RCFT may endure a large force over the design load, absorbed by displacement as a work according the equal-energy principle in Fig.32〔4〕. This principle can be applied to the structures using RCFS, RCFT or CFT. They can be designed to receive any size earthquake, avoiding collapse through their ductility.

Fig.29 Image of RCFT

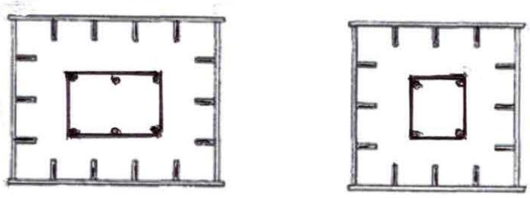


Fig.30 Reinforcing in RCFS


Fig.31 Compression test (left) and bending test (right) of RCFT

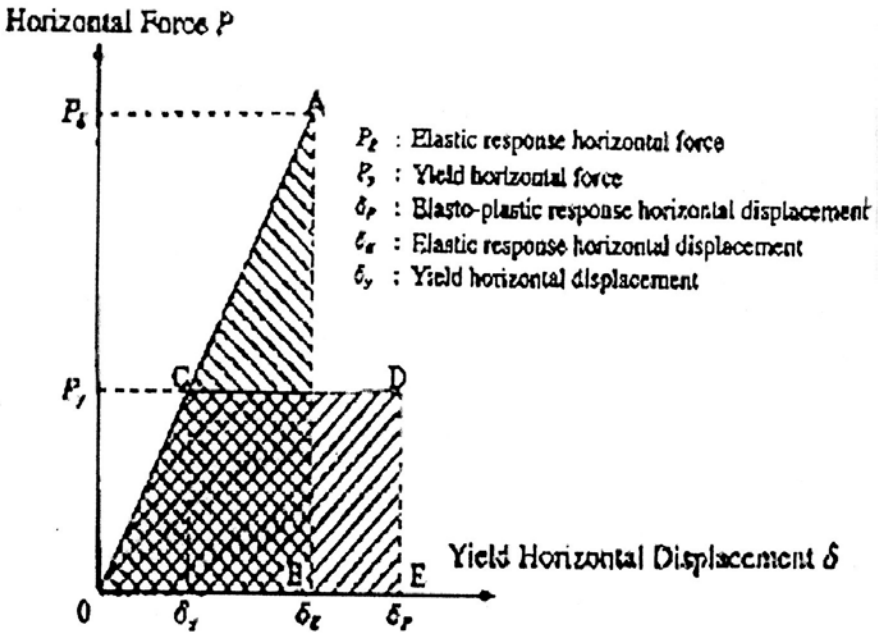



Fig.32 Concept of equal-energy principle



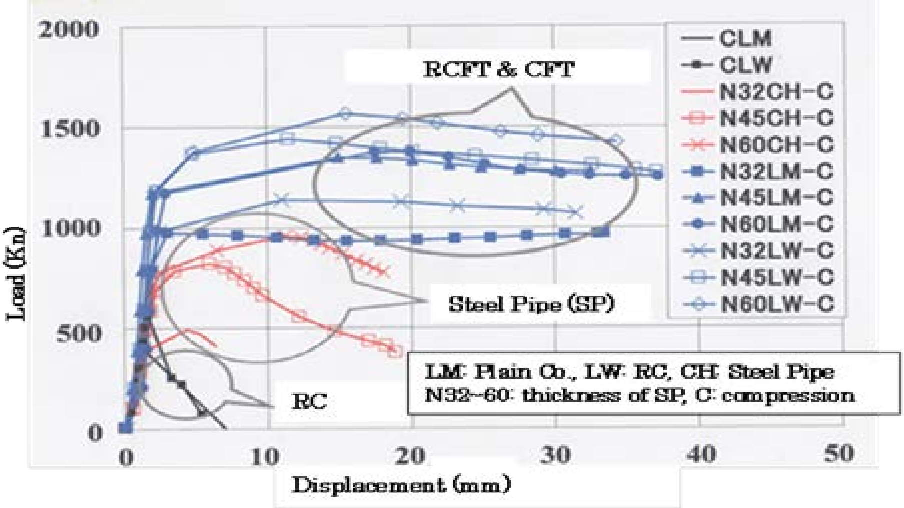



Fig.33 Load-displacement relationship among RCFT, CFT, SP and RC in compression test


Fig.34 Destroyed column specimen and concrete inside of double reinforcement

Fig.35 Destroyed squire specimen and concrete inside of double reinforcement

Fig.33 shows the results of compression test (C) on the test pieces of a plain concrete column (CLM), concrete column with double reinforcement (CLW), steel pipes (CH), CFTs (LM) and RCFTs (LW). The figures are the thickness of steel pipe. The curves of compression capacities of RCFT and CFT are corresponding to the sum of the maximum values of the steel pipe (SP) and RC. Since the load-displacement curves of RCFT and CFT take similar shape of the equal-energy principle, RCFT and CFT can sustain a few times of the yield force in Fig.32.

In the relationship between SP and RC in the RCFT, it is supposed that the RC is effective together with SP up to the maximum load $P_{max}$ of RCFT and the effect of ribs on the inner plate of SP is not identified. The presence of RC or plain concrete inside of the SP enables the RCFT or CFT to keep its maximum load carrying capacity in spite of a large deformation of the test piece. The specimens of RCFT and RCFS after the maximum load are given in Fig.34 and Fig.35. The shapes of the deformed RCFT and RCFS show buckling modes and the deformed inner RC not broken. RCFT in Fig.34 reveals the typical shear failure mode of the outer plate and shows the inner RC not broken in spite of the obvious shear failure mode. RCFS in Fig.35 expresses multiple buckling of outer plate and subtle deformation on the surface of inner concrete. The reason of these toughness may be due to the inner reinforcement cage in the center.

Fig.36 shows the results of bending test (B) on the specimens of steel pipes (CH), CFTs (LM) and RCFTs (LW) in normal steel pipe (N) and steel pipe with inner ribs (R), which is selected to examine a composited effect between steel pipe (SP) and concrete. The figures are the thickness of steel pipe. The maximum compression capacities of RCFT and CFT are corresponding to the sum of values of the steel pipe



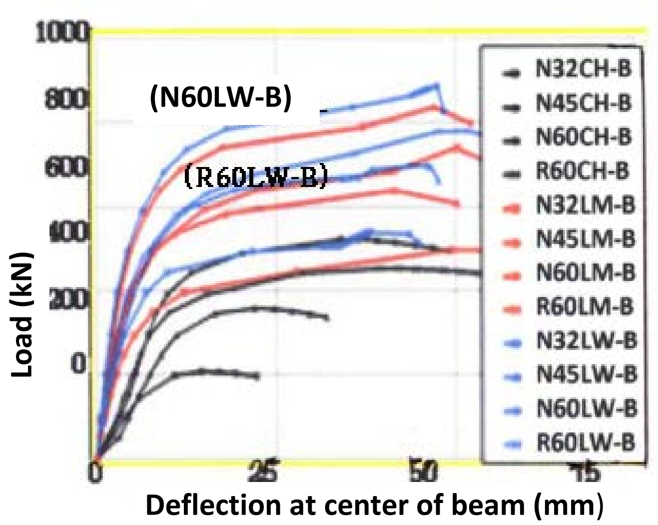



Fig.36 Relation between load & displacement at center of beam in bending test

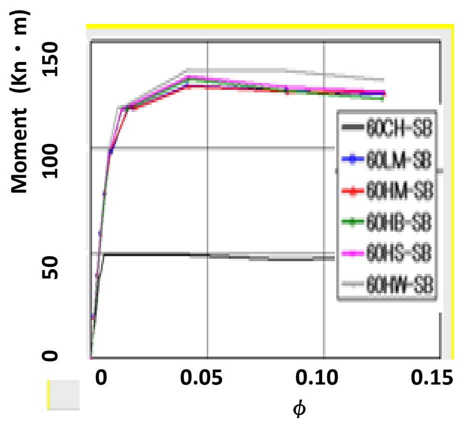



Fig. 37 Results of ding test for RCFT, CFT & SP with thickness of pipe of 6.0 mm

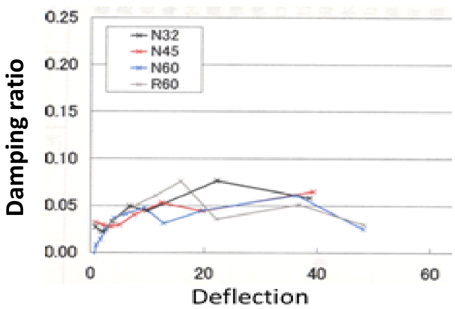



Fig.38 Damping ratio of RCFT


Specimen of inner RC in RCFT after bending test


Specimen of inner concrete in CFT after

Fig.39 Specimens of RC in RCFT and, of plain concrete in CFT

and RC. The specimens of a plain concrete beam and RC beam are omitted because of their negligible small stiffness for bending moment.

Since the load-displacement curves of RCFT and CFT take similar shape of the equal-energy principle, they can sustain a few times of the yield force in Fig.32 until a large deflection. The flexural capacities of RCFT and CFT are much larger than SP through the inside concrete. The compressive strength of confined concrete in the tube increases the stiffness of RCFT and CFT beams for the bending moment.

In Fig.36 the flexural capacity of RCFT is a little larger than CFT. It is considered that the shear strength of RCFT at the center is stronger than CFT and it yield a large extreme fiber stress. The flexural capacity of RCFT with the normal SP is larger than RCFT with inner ribs and the composited effect between SP and inside concrete is not observed. Fig.37 expresses the relation between the moment and the angle of deflection. RCFT, CFT and SP can follow the deflection of beam up to 0.15 radian. In the figure, CH is SP. LM, HM mean low & high strength concrete in CFT. HB, HS, HW are symbols of big, small & double cages in RCFT. RCFT and CFT have almost same behaviors in point of deformation. Fig.38 gives a series of equivalent damping ratio calculated from the hysteresis curves in the bending tests. The values of damping ratio are about 5 % in spite of the camber of deflection or the thickness of steel pipe.

RC and a plain concrete inside of RCFT and CFT after the bending test are introduced in Fig.39. The invisible cracks of RCFT specimen are traced with ink. In the case of CFT, two large cracks appeared at both places where the shear strains are at maximum, and many visible cracks remained. It was found that RCFT has better restoring capacity than CFT and it is possible to easily repair structural damage after a large earthquake. It means that RCFT can endure any large waves in a great earthquake with a deformation by a few times of design load and keep durability of structures even after a great earthquake.

## 5. conclusions

The following results from the studies on RCFT are gained as the conclusions.

(1) In the great earthquakes in the past many collapses of RC and steel structures had been caused by the sharp impact waves.

(2) Among the waves near the epicenter of large earthquakes the excessive waves over the gravity with very short period are occasionally observed on the relatively firm ground.

(3) The development of the accurate seismograph able to measure the waves with higher frequency is required for investigation of the mechanism of collapse by the excessive waves.

(4) Since the shear failure starts from the center of RC column, the reinforcement shall arrange at the center of cross section to prevent sudden collapse.

(5) The double reinforcement instead of the inner ties is effective for the shear strain and its assembly is easy to insert a prefabricated small cage inside of the outer cage using a crane.

(6) RCFT and RCFS were born as the excellent member to endure any large earthquake, exceeding RC, because the maximum strength of RC with a shear reinforcement is similar with the common RC.

(7) The performance of RCFT and RCFS follows the equal-energy principle.

(8) RCFT can largely deform itself keeping the maximum load and it has excellent restoring capacity though it can bend up to a camber of some degree.

(9) A large deformation of RCFT can absorb a few times of design load based on the equal-energy principle.

(10) RCFT has a damping ratio of about 5 %, relatively large as structural member.

(11) The central reinforcement of RCFT is essential to keep the inside concrete normal in long time, even after large earthquakes.

## Acknowledgements

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