Repairing and Retrofitting of Earthquake-Affected Exterior Beam-Column Connection by Using Resin Concrete

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ABSTRACT

Reinforced concrete structures may suffer a failure that caused by natural events such as earthquake. If the damaged building still can be used, then a repair (retrofitting) on the damaged section is highly necessary. Retrofitting materials that can be used is the polymer concrete. The purpose of this study was to determine the behavior of beam-column connections after repair (retrofitting) using polymer concrete. Test sample in the form of exterior beam-column connection with cross-sectional size of the column 30 x 30 cm, length of 3.5 m and the size of the beam cross-section of 17 x 30 cm, length 1.8 m, consists of 3 pieces. Experiment test method was based on ACI T1.1-01. All samples were tested in two stages, the first stage of the test until targeted damaged level which controlled by crack width of 0.4 mm. Furthermore, the test object repaired using normal concrete (BKN-1N) and polymer concrete (BKN-2R and BKN-3R). The second phase of test is done to collapse. Lateral force, deflection, and strain and crack pattern are observed. The data were processed to obtain the load-deflection relationship curve, stiffness, ductility ratio, energy dissipation and model of collapse. Beam-column joint behavior is compared with the acceptance criteria (ACI T1.1-01) to determine whether in accordance with the criteria required. Test results showed the value of the maximum lateral load test object BKN-1N, BKN-2R and BKN-3R,consecutively were 39.2 kN; 43.77 kN and 46.24 kN in the direction of curvature response (+) and the direction of curvature response (-), respectively for 59.1 kN; 62.73 kN and 69.91 kN. BKN-2R test objects have a greater ductility factor of 24.1% in the direction of curvature response (+) when compared with the test object BKN-1N. At the direction of curvature response (-), BKN-2R sample has a greater ductility 39.3% of the sample BKN-1N. Based on ACI T1.1-01, all samples have the response modification factor of 8. From SAP2000 modeling, BKN-1N, BKN-2R, and BKN-3R consecutively showed ability to withstand earthquake forces 3.36 times greater; 3.77 times; and 3.97 times greater than the earthquake forces are designed based on SNI 1726:2012. An advantage of using a resin concrete repair materials is very fast drying time.

Keywords: resin concrete, earthquake, repair, retrofitting, beam-column connection

1. INTRODUCTION

Reinforced concrete structure is applied in considerable amount on building construction in Indonesia. The component of the reinforced concrete can encounter failure that caused from natural events, for instance, earthquake. If the damaged building can be re-functioned, the retrofitting on the damaged part is really needed. One of the retrofit materials is concrete resin (Fakhruddin, 2013).

During repairing and retrofitting, two key aspects play important role, which is down time of the facilities and the technological affordances (Suhendro, 2012). This research is trying to provide the shortest retrofitting process and easy to apply by common workmanship level in Indonesia.

The purpose of this research is to discover the habit of beam-column connection after the retrofitting with concrete resin, including the load-deflection relation, envelope curve, hysteretic energy, collapse model, stiffness, ductility and crack pattern.

2. MECHANICAL PROPERTIES OF POLYMER CONCRETE

Jamshidi and Pourkhorshidi (2010) carried out a research on the mechanical properties of polymer concrete. The mixture composition used is shown in Table 1.

Table 1. Proportion of concrete mixture that used on the research (Jamshidi and Pourkhorshidi, 2010)

Mixture	w/c	Water (kg/m^3)	Cement (kg/m^3)	Polymer (kg/m^3)	Sand (kg/m^3)	Coarse (kg/m^3)	Density (kg/m3)
PC (Polymer concrete)	-	-	-	438	912	842	2192
NC (Normal concrete)	0.6	225	375	-	912	842	2215
DC (Durable concrete)	0.4	150	375	-	912	842	2215

2.1. Compressive strength

To discover the compressive strength value, cube sample with 150 mm side size was used. The sample was tested on day 7, day 28, and day 90 (see Figure 1(a)). The compressive strength of polymer concrete (PC) reached 100 MPa on day 7 of the test, then being relatively constant on the next days (Wijaya, 2015).

2.2. Flexural strength

The flexural strength value was measured with sample on 100×100×500 mm size. The result of the test can be seen in Figure 1(b). Flexural strength of the polymer concrete (PC) has different on each test time, unlike the durable concrete (DC) that has increased strength with time. The flexural strength of the polymer concrete (PC) was relatively constant in each test.

2.3. Splitting tensile strength

To discover the splitting tensile strength value, the sample used was cylinder sample with 150 mm diameter and 300 mm height. The result is shown in Figure 1(c). Splitting tensile strength of the polymer concrete (PC) was three times higher than the durable concrete (DC) on day 7 of the test. The splitting tensile strength value of the polymer concrete (PC) was relatively same on each time, yet the durability of concrete was increased with time.

2.4. Static modulus of elasticity

The sample used was cylinder sample with 150 mm diameter and 300 mm height. The result of the test is shown in Figure 1(d).

2.5. Rapid chloride permeability test

The method used to test the sample was based on ASTM 1202. The result can be seen in Figure 1(e). It shows that the polymer concrete (PC) has more strain compared to another type of concrete, and it is a suitable material to protect from the chloride attack.

2.6. Depth of water penetration test

The sample was used based on EN 12390-8 on time of day 7, day 28, and day 90. The result of the test is shown in Figure 1(f).

3. BASIC CONCEPT OF REINFORCEMENT

3.1. Structure Strengthening Alternative

Building structures suffering a failure due to earthquake can be repaired by applying three alternatives (Triwiyono, 2000; Imran&Hendrik, 2010), i.e:

a) Increasing strength
b) Increasing ductility
c) Increasing strength and ductility

3.2. Ductility

The building structure ductility factor (μ) is ratio of ultimate deviation and deviation at first yielding occurs; this can be shown in Equation (1) as follows:

$$\mu = \frac{\Delta_u}{\Delta_y} \tag{1}$$

Whereas μ is ductility, Δu is displacement from 80% of maximum structure, and Δy is displacement at first yielding.

3.3. Stiffness

Stiffness can be defined as the force needed to obtain one unit of displacement. The stiffness value is the slope angle from load and deflection relation. Stiffness can be explained from equation as follows:

$$K = \frac{P}{\Delta} \tag{2}$$

Whereas *K* is stiffness (kN/mm), *P* is force (kN), and Δ is displacement (mm)

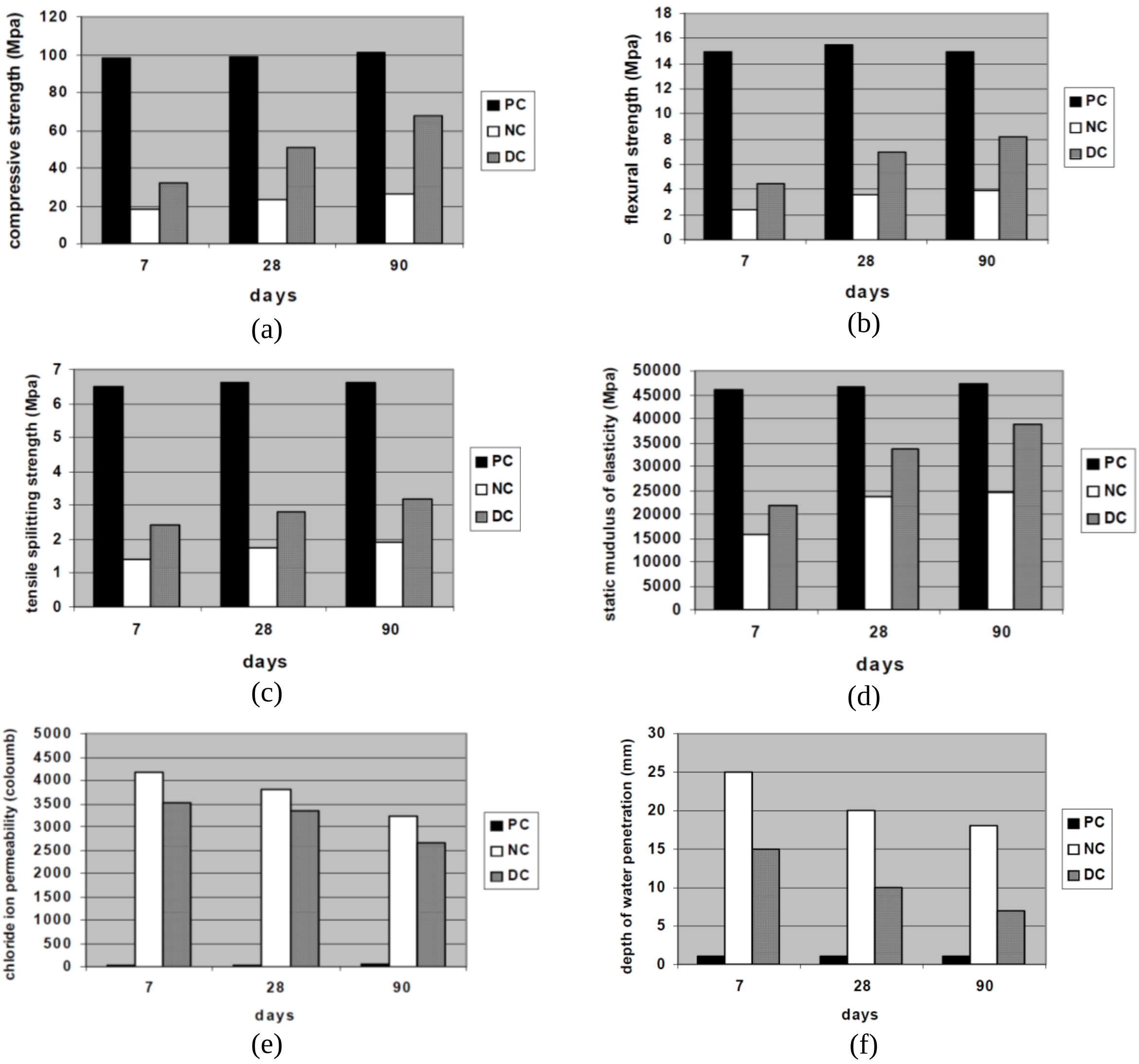


Figure 1. Mechanical Properties of Polymer Concrete, (a) Compressive strength, (b) Flexural strength, (c) Tensile splitting strength, (d) Static modulus of elasticity, (e) Rapid chloride permeability test, (f) Depth of water penetration test (Jamshidi and Pourkhorshidi, 2010)

3.4. Test Standard

The standards that needed to be fulfilled on beam-column connection tests are explained in ACI T1.1-01, Acceptance Criteria for Moment Frames based on Structural Test (ACI, 2001), which is as follows:

1) The sample should be subjected to a sequence of the displacement-controlled cycle that represents the expected drifts developed on connection when earthquake happens.
2) Three full cycles shall be applied at each drift ratio.
3) The initial drift ration should be within the essentially linear elastic response range of the sample. Subsequent drift ratios should be values not less than 1¼ times, ad not more than 1½ times, which is the previous drift ratio.
4) The test shall be continued by gradually increasing drift ratio until the minimum drift ration of 0.035 is achieved.

The data needed to quantitatively interpret the sample performance should be recorded.

4. RESEARCH METHOD

4.1. Design of Sample

The design of sample on this research was based on the application of common two-stories building. Calculation and internal force analysis conducted with the utilization of SAP 2000 software, in order to discover the amount of reinforcement needed for the research.

4.2. Test Sample

In constructing the sample, the scale 1:1 was used (Figure 2). The initial beam-column samples consisted of three units. Three of the samples were already been tested until targeted damage level which is controlled by. After the test, strengthening was conducted, which consists of three types, as follows:

a) One unit of beam-column reinforced concrete (with stirrup on joint), with strengthening by using normal concrete (BKN-1N).
b) One unit of beam-column reinforced concrete (without stirrup on joint), with strengthening by using resin concrete (BKN-2R).
c) One unit of beam-column reinforced concrete (without stirrup on joint), with strengthening by using resin concrete and addition of shear reinforcement or stirrup on joint (BKN-3R).

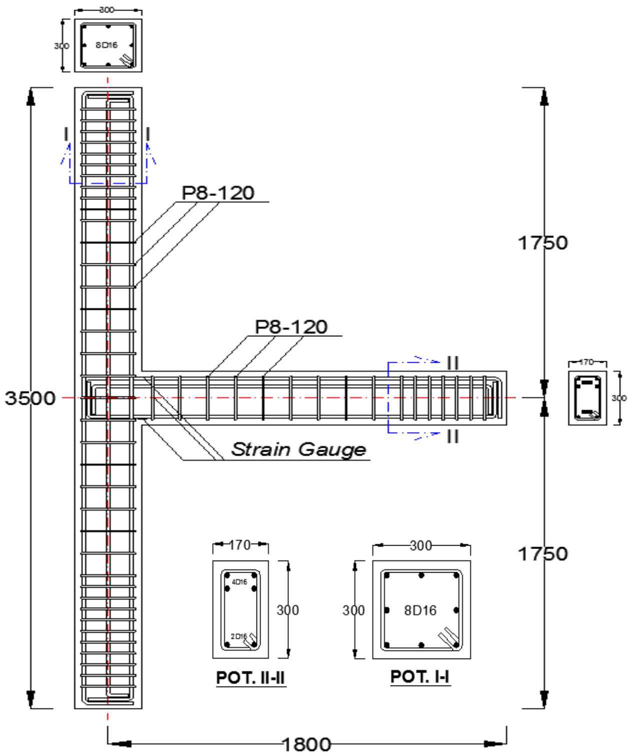


Figure 2. Details on sample reinforcement

4.3. Experiment Set Up

The sample was located on foundation and strapped on both columns. Foundation on the end of a column has hinge character, and on the other end has roll character. The end of the beam was a free end, and act like a cantilever with 1500 mm arm length. On one end of the column axial force of 180 kN was conducted. On the end of the beam gradual alternating force was conducted, as according to the test method on ACI T1.1-01. Two LVDTs was placed on the end of the beam, each 1 unit in every loading direction. One LVDT was placed on the end of the column to see any movement occur.

5. RESULT AND DISCUSSION

5.1. Hysteretic Loops

According to Figure 3, sample BKN-3R absorbed higher energy compared to two other samples on some of the drift in the end of test (drift 10 (2.75%) to drift 13 (6.75%)). This was happened because on sample BKN-3R, damage only occurred on the beam, and not channeled to the column, when loading was conducted on some of the last drifts. The column became stronger after retrofitting, so when the beam has collapsed, the one who held the load on the some of the last drifts was the beam flexural reinforcement that channeled to the column. Different from the other two samples, on drift 10 (2.75%) BKN-1N and BKN-2R, damage on the beam channeled to the column, which then caused crack on the column. The energy absorbed by the structure was decreasing when the column started collapsing. Hysteretic loops can be seen at Figure 4.

5.2. Envelope Curve

Figure 4 shows that the load was higher at the time of crack, yield, or peak of samples retrofitted by resin concrete (BKN-2R and BKN-3R), compared to sample that used normal concrete (BKN-1N). It is noted that the lateral load on curvature response direction (+) of sample BKN-2R was 11.7% higher and 18% higher with sample BKN-3R, in peak condition, when compared with sample BKN-1N repaired by normal concrete. The lateral load on curvature response direction (-) was higher 6.1% for sample BKN-2R and 18.3% higher with sample BKN-3R in peak condition. It can be seen that addition of stirrup gave effect to the addition of load capacity on joint.

5.3. Initial Stiffness

Figure 5 depicts the difference of envelope curve and initial stiffness of three of the samples before and after retrofit. The comparison was conducted until drift 4 (0.5%), for on that particular drift, the sample test on the samples on the first stage before the retrofit conducted was stopped. The first stage test was stopped when the flexural reinforcement on the sample was near the yielding.

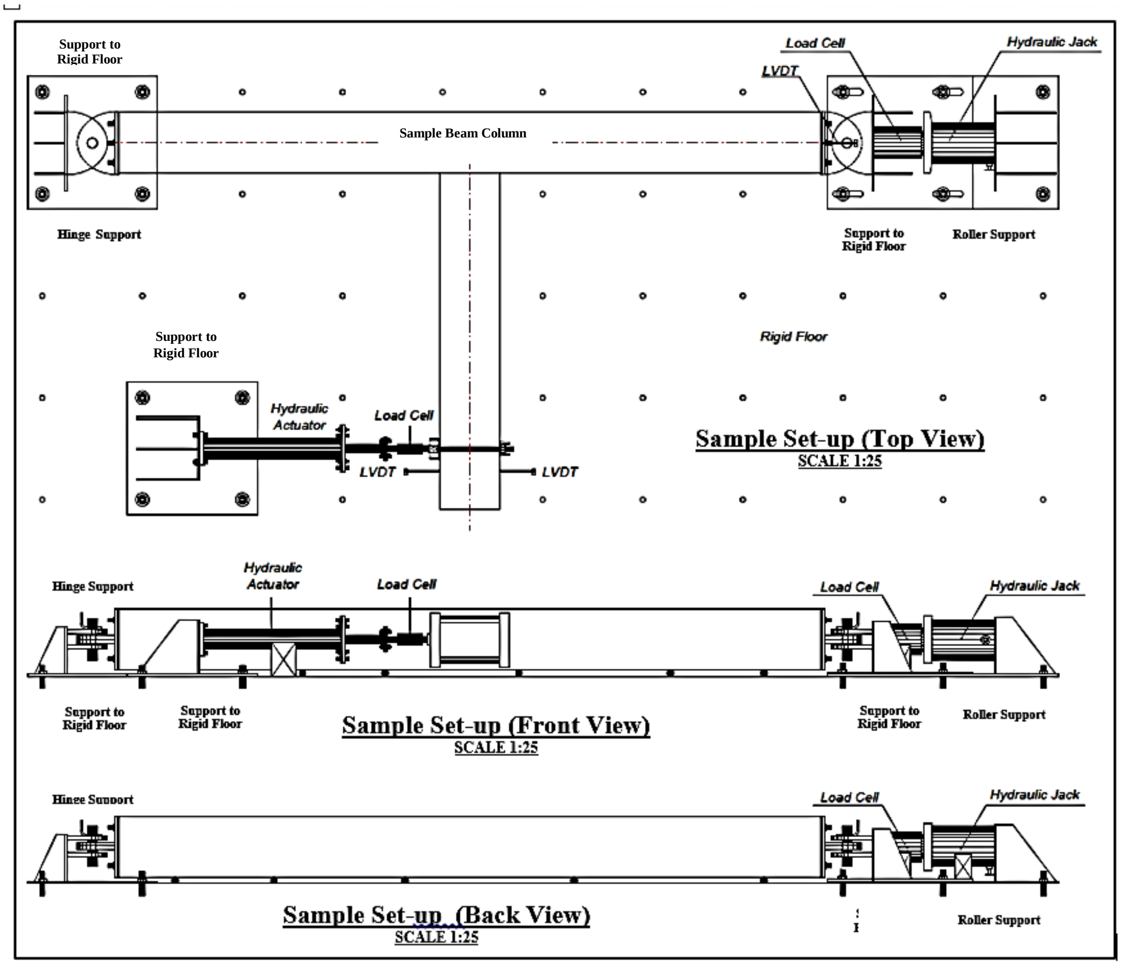


Figure 3. Sample

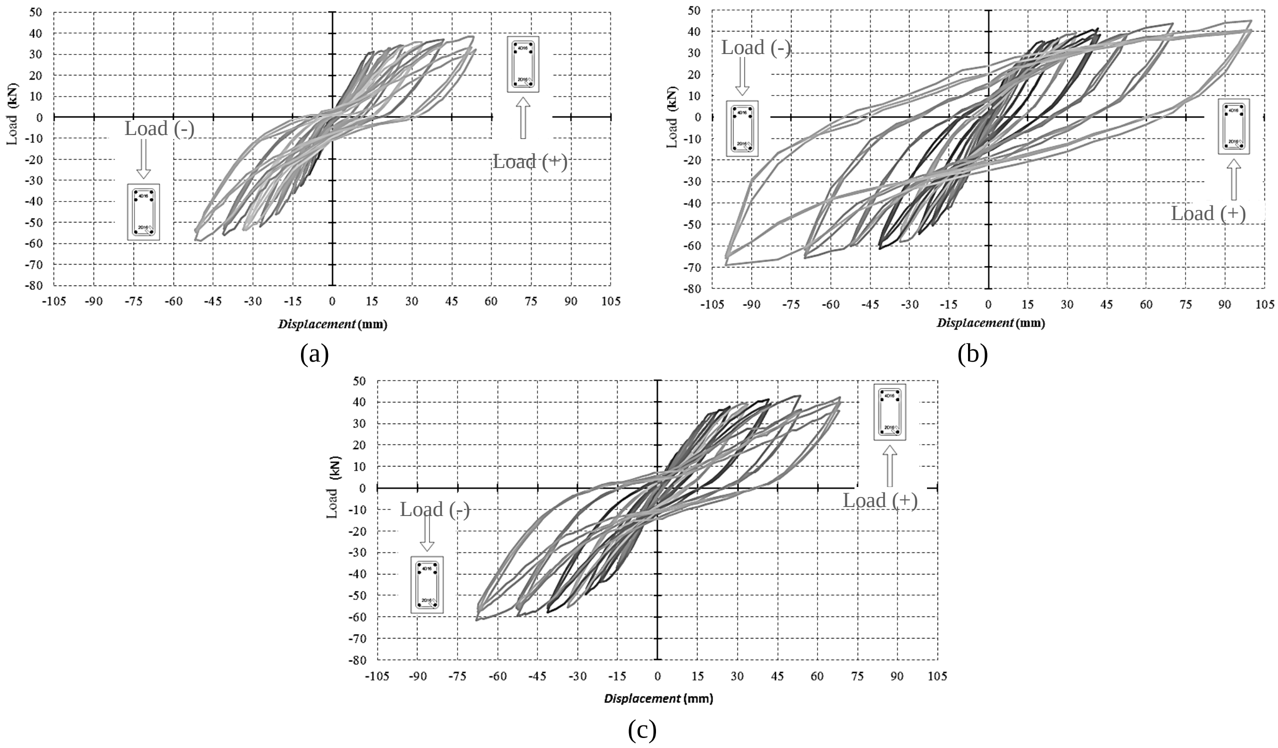


Figure 4. Hysteretic loops of sample, (a) BKN-1N, (b) BKN-2R, (c) BKN-3R

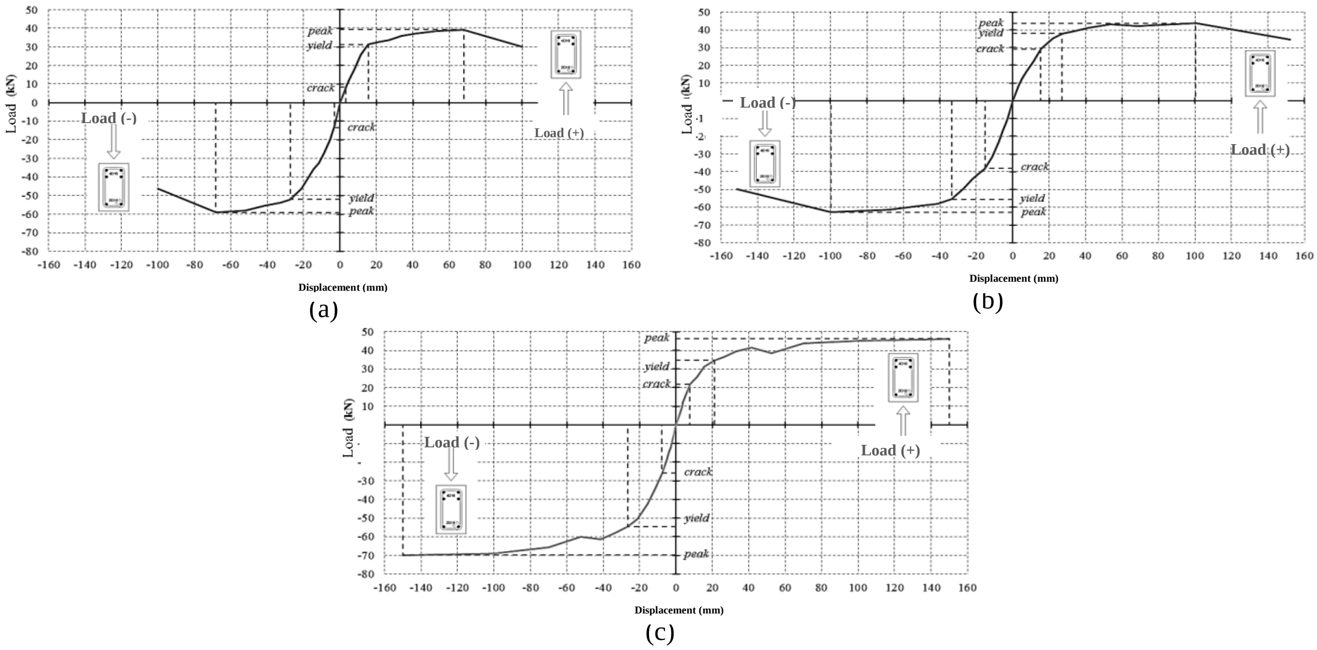


Figure 5. (a) Envelope curve BKN-1N, (b) Envelope curve BKN-2R, (c) Envelope curve BKN-3R

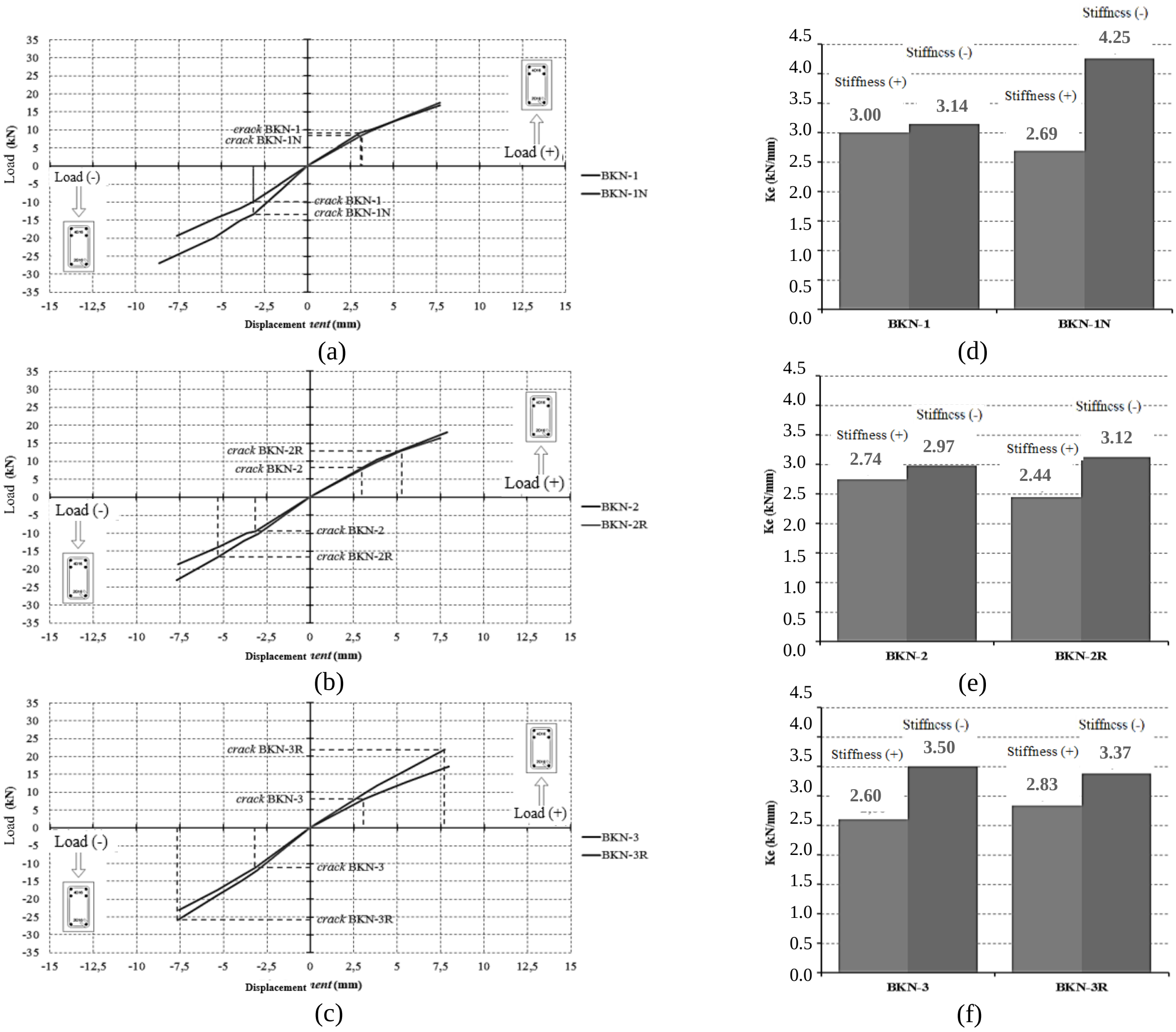


Figure 6. Initial stiffness of all three samples before and after retrofit, (a) Envelope curve difference of first sample, (b) second sample, (c) third sample, (d) Stiffness difference of the first sample, (e) second sample, (f) third sample.

Initial stiffness was calculated based on the laboratory observation when sample experienced crack that can be seen at Figure 6. The stiffness value number can go up and down after retrofitting. Several factors that made the stiffness value varied are as follows:

a) Foundation of samples did not function well.
b) Unstable hydraulic when the load was placed.
c) The material property used for the retrofitting was different from the property of the initial sample.
d) Imperfect casting may lead to porous concrete.
e) Adhesion between old and new concrete was not perfect.

5.4. Ductility

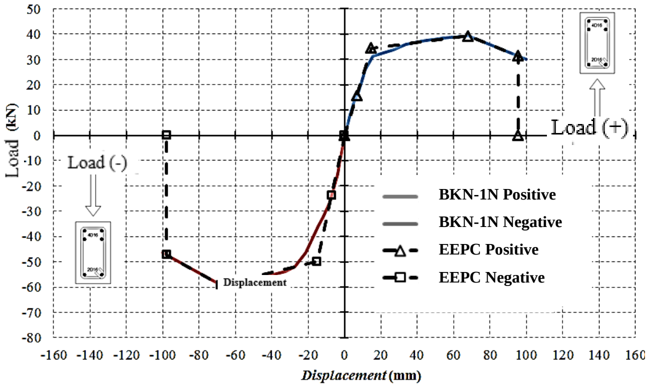
The samples repaired by using resin concrete (BKN-2R) has higher ductility factor than the one applying concrete (BKN-1N), both on the curvature response direction (+) and the curvature response direction (-) as shown in Table 2. The ductility value number for sample BKN-3R could not be discovered because the sample was not tested up to failure. The sample test BKN-3R was stopped on account of limitation on the instrument.

Table 2. Displacement and sample ductility factor

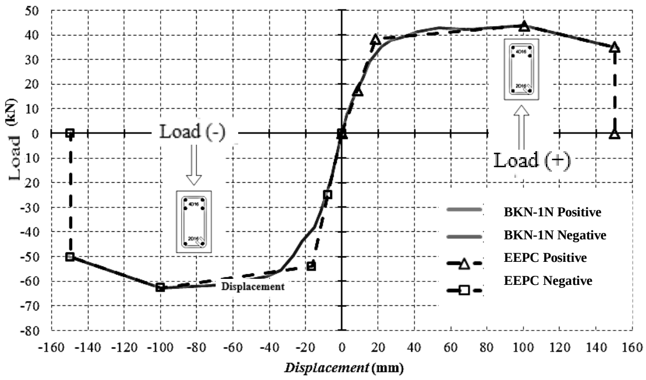
Test	Response direction	Deflection of failure, Δu (mm)	Deflection of yield, Δy (mm)	Ductility factor, μ=Δu/Δy
BKN-1N	Load(+)	95.45	14.65	6.52
	Load(-)	-97.92	-15.09	6.49
BKN-2R	Load(+)	150.34	18.58	8.09
	Load(-)	-149.56	-16.55	9.04
BKN-3R	Load(+)	-	-	-
	Load(-)	-	-	-

5.5. Equivalent Elastic-Plastic Curve (EEPC)

The Equivalent Elastic-Plastic Curve (EEPC) analysis is to obtain the parameter of load-displacement relation at the time of crack, yield, peak, and failure, as the basis of ductility calculation. It can be seen at Figure 7 and Table 3.



(a)



(b)

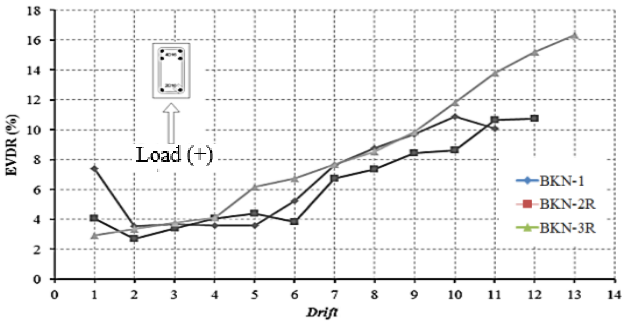
Figure 7. (a) EEPC of sample BKN-1N, (b) EEPC of sample BKN-2R

5.6. Equivalent Viscous Damping Ratio (EVDR)

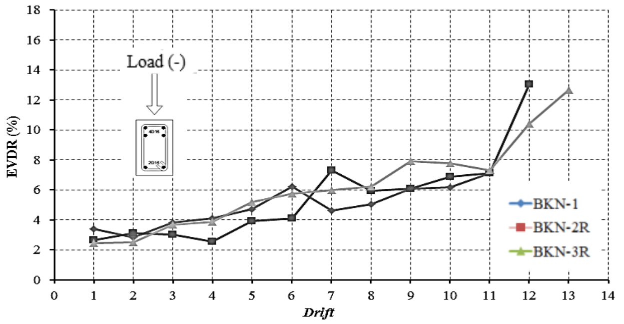
Equivalent viscous damping ratio is a description of the magnitude of structural damping in receiving the external load. According to Paz (1985), recited in Paz (2007), the damping ratio in structure system is usually less than 20 %($\xi < 0.2$). Figure 8 showed that in this test the repaired samples using resin concrete and normal concrete have damping ranged from 2% to 16%.

Table 3. EEPC value on each sample

Condition	BKN-1N				BKN-2R				BKN-3R			
	Load (+)		Load (-)		Load (+)		Load (-)		Load (+)		Load (-)	
	Load (kN)	Displ. (mm)	Load (kN)	Displ. (mm)	Load (kN)	Displ. (mm)	Load (kN)	Displ. (mm)	Load (kN)	Displ. (mm)	Load (kN)	Displ. (mm)
Crack	15.68	6.67	-23.64	-7.15	17.51	8.50	-25.09	-7.68	18.50	6.43	-27.96	-8.62
Yield	34.43	14.65	-49.93	-15.09	38.30	18.58	-54.07	-16.55	-	-	-	-
Peak	39.20	67.92	-59.10	-68.21	43.77	100.30	-62.73	-99.87	46.24	150.00	-69.91	-150.00
Failure	31.36	95.45	-47.28	-97.92	35.02	150.34	-50.18	-149.56	-	-	-	-



(a)



(b)

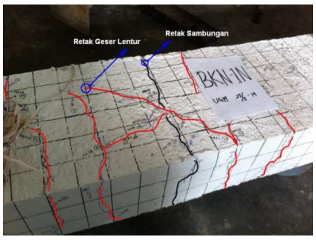
Figure 8. (a) EVDR on curvature response direction (+), (b) EVDR on curvature response direction (-)

5.7. Crack Pattern

In general, the largest track happened in the beginning part of the beam or the plastic hinge area. At the connection of old concrete (normal concrete) and new concrete (normal concrete or resin concrete), the crack occurred was not really large. All three samples showed similar crack patterns.

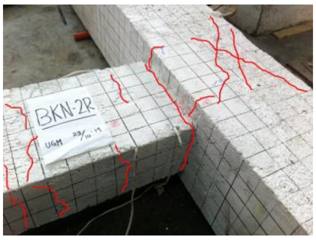
The collapse happened in the beam-column connection did not meet the mechanism of “strong column weak beam”. From the conducted test, sample BKN-1N (see in Figure 9(a) thru Figure 9(c)) and sample BKN-2N depicted in Figure 9(d) thru Figure 9(f) undergone damage on the column when reached the maximum load, and caused the concrete went to the joint spalling area. As for the sample BKN-3R (Figure 9(g) thru Figure 9(f)), it was not known whether it meets the mechanism of “strong column weak beam” or not because the test was stopped on the account of t instrument limitation.

(a)



(b)

(c)



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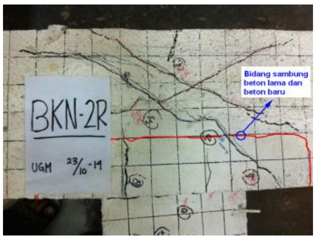
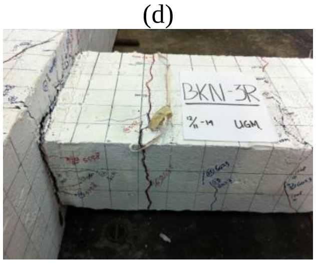
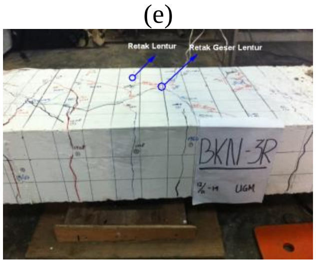


(e)

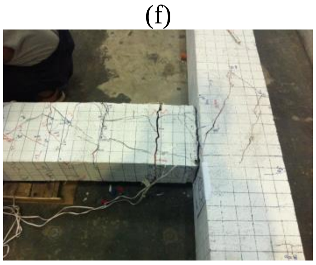
(f)



(g)



(h)



(i)

Figure 9. Crack pattern of sample BKN-1N, (a) Drift 7 (1.4%), (b) Drift 10 (2.75%), (c) Maximum load; Crack pattern of sample BKN-2R (d) Drift 9 (2.2%), (e) Drift 11 (3.5%), (f) Maximum load; Crack pattern of sample BKN-3R, (g) Drift 10 (2.75%), (h) Drift 10 (2.75%), (i) Last condition

5.8. Acceptance Criteria for Testing

From the result of conducted experiment, the acceptance criteria were obtained, as the ACI T1.1-01 required, which is:

a) The sample shall have attained the minimum lateral strain (E_n) before its drift ratio is 2%.

Table 4 showed that the lateral load test on drift 1.5% on each sample was exceeded the lateral strain of the sample itself. In this case, each sample has met the requirement.

Table 4. Lateral strain of sample and lateral load test before drift 2%

Sample	Response direction	Lateral strain of sample (kN)	Lateral load of 1.75% drift test kN)
BKN-1N	Load(+)	27.74	33.80
	Load(-)	44.44	52.10
BKN-2R	Load(+)	29.43	37.91
	Load(-)	51.21	49.44
BKN-3R	Load(+)	29.43	36.63
	Load(-)	51.21	54.52

b) Maximum lateral strain recorded on sample test shall not exceed λEn, whereas λ = 1.58.

λ is a ratio between reinforcement steel tensile strength and actual yield strength. Based on the results in Table 5, the lateral load test of the sample with normal concrete (BKN-1N) and one with resin concrete (BKN-2R and BKN-3R) did not exceed the required maximum lateral strain on sample.

Table 5. Maximum lateral load of sample and lateral strain

Sample	Response direction	Lateral strain of sample (kN)	Maximum lateral load (kN)
BKN-1N	Load(+)	43.83	39.20
	Load(-)	70.22	59.10
BKN-2R	Load(+)	46.50	43.77
	Load(-)	80.91	62.73
BKN-3R	Load(+)	46.50	46.24
	Load(-)	80.91	69.91

c) As for the cyclic load on maximum drift level, the one that was used as reference shall not have less value than 3.5%.

From the conducted test, the three samples reached the test level drift more than 3.5%. In this case, all three samples meet the requirement. The other thing that became a requirement is the characteristic of the third cycle on maximum drift level should meet the qualification such as the peak force for given loading direction on the sample should not less than 0.75 E_{max}, for the same loading direction (see Table 6); the relative energy dissipation (β) which is the comparison ratio of hysteretic loop (A_h) of the third loop on maximum drift level with extents (E1+E2)(θ1'+θ2') that is marked with dotted line in Figure 10 is not less than 1/8, and the secant stiffness that connects drift ratio point of -0.0035 to drift ratio of +0.0035, is shall not less than 0.05 times the initial stiffness.

Table 6. Peak force of third cycle on maximum load drift

Sample	Response Direction	0.75 Top Force (Emax) Examination	Top Force in Third Cycle
BKN-1N	Load (+)	29.40	35.2
	Load (-)	44.33	54.0
BKN-2R	Load (+)	32.83	36.0
	Load (-)	47.05	56.3
BKN-3R	Load (+)	34.68	40.1
	Load (-)	52.43	64.8

Table 7. Comparison on stiffness value

Sample	Response Direction	Stiffness - 0,35% s/d +0,35% (kN/mm)	First Stiffness x 0,05 (kN/mm)
BKN-1N	Load (+)	0,120	0,118
	Load (-)	0,368	0,165
BKR-2R	Load (+)	0,129	0,103
	Load (-)	0,220	0,163
BKR-3R	Load (+)	0,398	0,144
	Load (-)	0,295	0,162

Peak force of the third cycle for each sample as shown in Table 6 exceeded 0.75E_{max} value. In Table 7, it is shown that relative energy dissipation of each sample was higher than 1/8, while in Table 8, all sample meet the requirement on stiffness value (above 0.05 of initial stiffness).

Table 8. Relative energy dissipation of sample

Sample	Drift (%)	Ah (kN.mm)	E1 (kN)	E2 (kN)	ϴ'1 (mm)	ϴ'2 (mm)	Dissipation of Relative Energy (ß)
BKN-1N	3.50%	1110.11	32.20	54.00	40.34	35.50	0.170
BKN-2R	4.50%	2001.00	36.01	56.31	49.17	50.35	0.218
BKN-3R	6.75%	7272.35	40.06	64.76	86.08	80.04	0.418

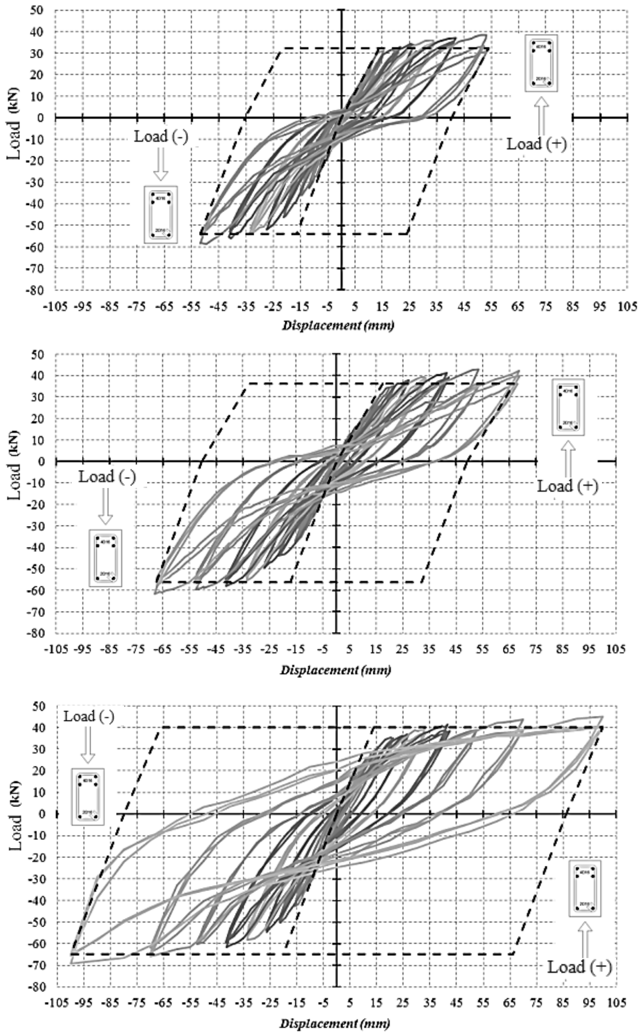


Figure 10. Relative energy dissipation of all three samples, (a) Relative energy dissipation of BKN-1N, (b) Relative energy dissipation of BKN-2R, (c) Relative energy dissipation of BKN-3R

Based on ACI T1.1-01, if all requirements from (a) to (c) has been fulfilled, the response modification factor (R) of maximum 8 can be used (Tsonos, 1999). In this research, all three samples, whether the one with normal concrete (BKN-1N) or with resin concrete (BKN-2R and BKN-3R) has meet all the requirements. However, in the calculation of the nominal face value (E_n) of sample with resin concrete (BKN-2R and BKN-3R), the calculation used the method for normal concrete. In this research, the response modification factor (R) of sample BKN-2R and BKN-3R cannot be certainly accepted, because research needs to be conducted first, in order to find fully complete resin concrete property and method to calculate the capacity of resin concrete cross section. If the method to calculate the capacity of resin concrete cross section already exists, then the calculation for lateral strain value (E_n) needed to be re-conducted and checked if it already fulfilled the ACI T1.1-01 requirements. By checking it, then it can be fully known whether the value (R) of sample BKN-2R and BKN-3R still of 8 or less than 8.

5.9. Retrofitting Capacity of Joint that Uses Resin Concrete in order to Withstand Earthquake Forces on Location

In the modeling process of the sample in order to find the retrofitting capacity using the resin concrete, software SAP2000 was used. In SAP2000, the multiplier factor of earthquake strength was tested with trial and error method, until it was obtained the moment value that was almost similar to the moment that damaged the sample in the laboratory test. The multiplier factor of earthquake strength that was based on SNI 1726:2012 was obtained from result of importance factor (I) = 1, times with gravity acceleration(g) = 9.81 m/s^2, divided by earthquake reduction factor (R) = 5; it resulted then in earthquake strength multiplier factor based on SNI 1726:2012—of 1.962.

Table 9. Earthquake strength multiplier factor that damaged the samples

Sample	Magnification Factor	Moment (+) (kNm) Experiment	Moment (+) (kNm) SAP 2000	Moment (-) (kNm) Experiment	Moment (-) (kNm) SAP 2000
BKN-1N	6.6	52.92	52.54	79.79	60.78
BKN-2R	7.4	59.09	59.22	84.68	67.46
BKN-3R	7.8	62.42	62.57	94.38	70.81

Table 9 showed that the sample BKN-1N can hold 6.6/1.962 = 3.36 times earthquake force that was designed based on SNI 1726:2012. While as for the sample BKN-2R and BKN-3R can hold the earthquake force that was designed based on SNI 1726:2012, consecutively of 3.77 times and 3.97 times.

6. CONCLUSIONS AND SUGGESTIONS

6.1. Conclusions

From the conducted research, several points can be concluded:

a) Maximum lateral load on the samples with resin concrete (BKN-2R and BKN-3R) was higher than normal concrete (BKN-1N). The value of maximum lateral load of sample BKN-1N, BKN-

2R and BKN-3R in consecutive are 39.2 kN; 43.77 kN and 46.24 kN; on curvature response direction (+) and on curvature response direction (-), consecutively are 59.1 kN; 62.73 kN; 69.91 kN.

b) The sample repaired with resin concrete has higher ductility factor than normal concrete. The sample BKN-2R has higher ductility factor of 24.1% on curvature response direction (+) when compared with sample BKN-1N. On the curvature response direction (-), sample BKN-2R has higher ductility factor of 39.3% than the sample BKN-1N. Ductility factor on sample BKN-3R could not be discovered, because it did not being tested up to failure, on the account of instrument limitation.

c) In this research, sample BKN-1N and BKN-2R did not meet the strong column weak beam mechanism, as seen from the collapse pattern. The sample BKN-3R was not known whether it meets the mechanism of strong column weak beam or not because it did not being tested up to failure, on the account of instrument limitation.

d) All of the three samples fulfilled the entire test required in ACI T1.1-01, so the response modification factor (R) of maximum 8 can be used. In the calculation of lateral strain value (E_n) of sample BKN-2R and BKN-3R, the approach used was normal concrete calculation method, because the method to calculate the resin concrete cross section was not available.

e) From the modeling with SAP2000, sample BKN-1N could hold earthquake force 3.36 times higher than based on SNI 1726:2012. The sample BKN-2R could hold earthquake force 3.77 times higher than the earthquake force designed based on SNI 1726:2012; and the sample BKN-3R could hold earthquake force 3.97 times higher than the earthquake force designed based on SNI 1726:2012.

6.2. Suggestions

A few suggestions that can be used for the next research are as follows:

a) It is needed to add one more control beam tested up to ultimate load, in order to be a comparison to the test result of retrofitting and strengthening beam.

b) Further research is needed, particularly on the subject of the effect on resin polymer concrete application as retrofitting and strengthening material on the joint with yielding reinforcement.

c) Further research is needed to produce equations that are especially used to make theoretical calculation on concrete cross section capacity.

d) At the laboratory test, the amount, capacity, and condition of the instrument used need to be checked first, in order to be able to plan a better experiment set up.

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