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Seismic Retrofitting RC Structures with Precast Prestressed Concrete Braces-ABAQUS FEA Modeling

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ABSTRACT

Precast prestreesed concrete braces are a new method for seismic strength of Concrete Structures which has the following benefits: a) no wet concrete work in construction site b) no bolt or anchorage to the existing frame c) easy to apply d) short construction period e) low construction cost; to evaluate seismic performance of strengthened structure. A model consist of existing frame and concrete braces were created using ABAQUS (nonlinear-finite element) software. Comparison existing and strengthened frame showed that braces are effective in lateral drift decreasing. Study concrete compressive strength on seismic behavior of brace showed that when compression strength of brace is lower than existing frame; retrofitting system has low stiffness and wasn't effective in reducing lateral drift. But, in specimen with compressive strength ratio (brace to frame) two times or more, braces showed high strength and stiffness.

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1. INTRODUCTION

There are different ways for seismic strengthening RC Structures, each of those has its advantage and limitations. Structure frames with Brace rather than other structures such as moment frames or shear walls, is an effective and valuable way for retrofitting against lateral loads (earthquake and wind) because incline members act as truss which bears tensile and compression tensions. This axial performance is reducing moments and concludes smaller column and beam cross sections in comparison with similar moment frames. This method is widely used in steel frames and its benefits encouraged structure engineers to try braces in concrete frames too.

However, adding steel braces to concrete moment frame has lots of difficulties for connecting brace to the frame and its seismic behavior [1-6] is not correctly known. But it's benefits and great performances of braces is encouraging engineers and researchers to put more efforts. There has been lots of research for using steel braces in RC frames [1, 7] recently and it is an accepted method of seismic retrofitting RC structures but using concrete braces for seismic retrofitting because of homogeny and same material properties of concrete braces and RC frame could lead to better seismic behavior in compare to the steel braces. when frame and brace are made from the same material (concrete), it may lead to better seismic and nonlinear behavior and failure mode of the strengthened frame. However, concrete less tensile resistance is made it difficult and challenging to be used as an inclined member (brace). Concrete fundamental weakness is in tensile and its tensile resistance is very much less than its compressions resistance. (about 0.1) [8] prestressing members and unbounding braces in tensile and to consider tensile strength of rebar's in braces are some ways to partially cover this weakness of concrete braces.

2. NOVILTY

The aim of this research is to study a new method of bracing system (precast prestressed concrete braces) which is proposed by WATANABE and his partners [9, 10] for seismic retrofitting RC structures.This proposed method needs no work with wet concrete in site and

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doesn't need to be anchored or bolted to the existing frame which will lead to faster and more economic accomplishment.This research tends to study applying concrete braces for seismic retrofitting and to know it's limitations and difficulties of problems; then search some solutions for high performance of this method. During this proceed at first a computer simulated model was made by ABAQUS FEA (Finite Elements) software to examine experimental (WATANABE work) with analytical results (software). Then, study dissipation energy by the system and reduction of lateral displacements which indicate whether this proposed system is suitable.

3. INTRODUCTION TO THE PPCB

Watanabe and his partners [9, 10] firstly proposed an intelligent and new method of seismic retrofitting concrete structures with concrete braces which has following features: The X shape brace which is consist of four precast concrete members that is assembled in the site and prestressing force is applied through the end members (Figure 1). Gap between brace and frame by a high performance none-shrinkage mortar is filled after hardening of mortar then prestresse force will be released. The brace legs will extend and placed tightly in the frame.

By assembling precast members (Figure 2) and placing it in the frame and filling the gap by high performance none-shrinkage mortar at bottom corners and place L shape plate at the top corner, brace is placed in frame. Figure 3 shows that The X-shape concrete brace placed in the existing frame and Enough openings still exist. Figure 4 shows lateral force resisting mechanism.

When RC frame with brace is exposures to lateral loads only one of its leg is effective in compression, without applying prestress force diagonal tensile member would be separated from the frame. Because of the concrete tolerates are very small amount of tensile force, to prevent separation of the member a device is used which is made of Flat springs and steel pipe that is called FSSP (Flat Spring and Steel Pipes) device. (Figure 5).

The FSSP device is installed at the end of the both diagonal members which produce a small amount of compression force even if the member is due tensile force.

Figure 1. Introduction of prestressing force to the lower part of a diagonal member

Figure 2. Erection of the brace

Figure 3. The X-shape concrete brace placed in the existing frame (Enough openings still exist.)

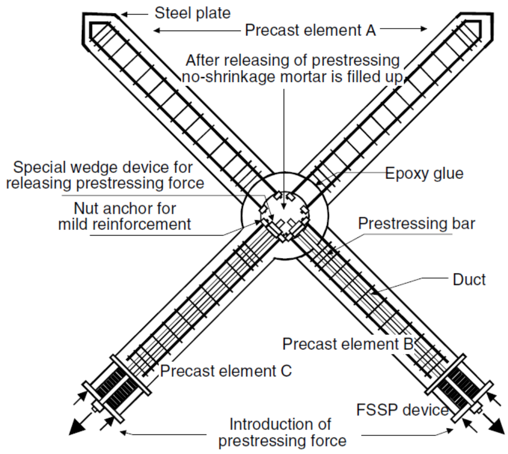

Figure 4. Lateral force resisting mechanism and design items and its reinforcement

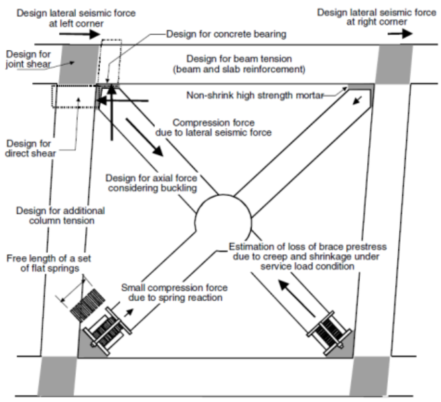

Figure 5. Assembled precast concrete brace

Even in tensile there is still specified amount of compression force can be applied while FSSP device is in compression. Therefore, both members are in compression during the response to lateral loads. This is the mechanism of resistant of X-shape brace with FSSP to the lateral load.

WATANABE and partners study two prototype frame with the proportion ratio 1 to 2 to the actual frame. The primary results showed the concrete brace is proper in reducing lateral displacement due to lateral loads [9].

4. MODELING USING ABAQUS (FINITE ELEMENT SOFTWARE)

4. 1. Frame and Brace Properties The peripheral frame with the proportion ratio 1 to 2 was the simulated frame at the bottom of a four story RC building which is designed by an old Japanese code (1980) and due to studies made needs to be seismically retrofitted [9]. Column section is 300x300 mm with 16 longitudinal D10 rebar and beam section is 325x275 mm with 4 D10 rebar at top and bottom each (Figure 6). Concrete brace number 1 (No. 1) section is 100x120 and the anticipated failure mode is brace buckling. Concrete brace number 2 (No. 2) section is 120x150 and anticipated failure mode is direct shear at the end of the column or beam [9] collar shear rebar is D4 by 70mm space in columns and 100mm in beams and 50mm in braces and 50mm in foundation beam. Foundation beam section is 325mm height and 500mm width with 16 D10 longitudinal rebar (8 top, 8 butt) and shear D4 with 50mm distance space. The X-shape brace is consisting of 5 members: leg 1, leg 2, middle section. These five members are precast and would have sent to the site then assembled. At the end of the leg 1 of brace there is a L-shape steel plate for preventing demolition at the joints. Brace longitudinal bar is 6 D6 and shear bar is 3 with 50mm distance space (Figure 7).

The middle section: The middle secon is connected to the leg 1, leg 2 by 4 D6 bar which are placed in the middle section before pouring concrete. By inserting these bars into the wholes which are made before trough the leg 1, leg 2 the members are put correctly and tightly in place, then wholes filled with grout and there would be a proper connection between leg 1 and middle section and leg 2.

None-shrinkage high strength mortar: By assembling four precast members of brace and after applying prestress force, the brace would be placed in the frame and the space remain between FSSP and frame is filled with none-shrinkage high-strength mortar. This mortar should have the proper compression and after hardening should perform properly and conduct compression forces from frame to brace. This mortar should have minimum shrinkage to not case the prestress losses or dispatch of the brace.

The L-shape end plate: At the end of the leg 1 of brace for preventing demolition of concrete at the joint of brace and frame a L-shape steel plate with 200mm x 150 mm dimension and 150 width is used.

FSSP device: FSSP device is consist of steel pipe and flat springs (Figure 8). The total stiffness provided by springs is 2.5 KN/mm, when a 25KN load is applied to device the bearing plate touch the steel pipe. This steel pipe is designed to provide sufficient for axial compression even if the diagonal member No. 2 is failed due to compression. Diameter of steel pipe is 104mm and thickness of it is 20mm.

The FSSP device is modeled with two parallel steel plate 170 mm x 140 mm with 20mm thickness with 140mm space toward each other and with four spring with similar stiffness so that the total stiffness provided is 2.5 KN/mm (Figure 9).

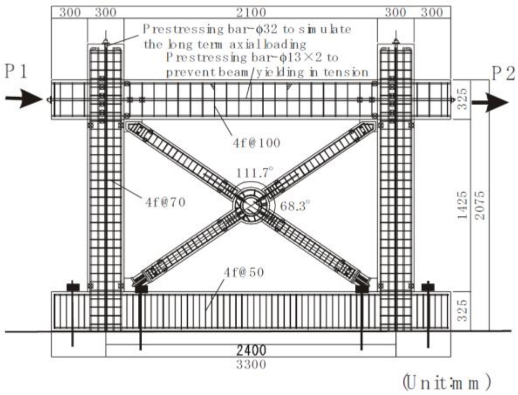

Figure 6. One story frame dimentiones

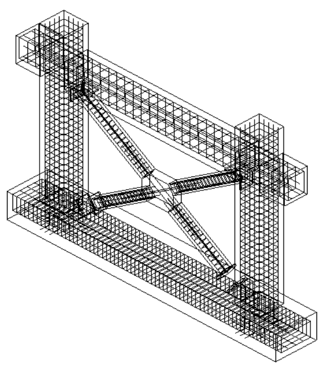

Figure 7. 3D picture of frame and brace modeled in ABAQUS No.1 and No. 2 speciments

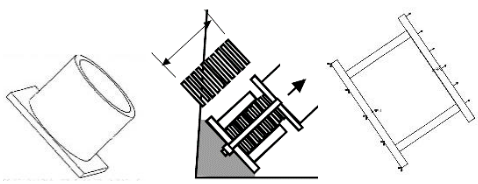

Figure 8. FSSP device

Prestressed cable: to considering gravity loads of top stories while applying lateral load prestressed cable were used in columns. prestressed applied load is 324 KN trough the Ø32 prestressed steel bar [9]. Similarly beam is prestressed with two unbound prestressed steel bar Ø13 with applied load 300KN.

4. 3. Applying Lateral Load and How to Measure

a) Experimental Work

WATANABE and partners method used for applying lateral load is indicated in Figure 10. Two similar horizental loads P1, P2 at the end of the frame (consoule beam) with to hydraulic jack is applied.then after the beam yielding in tensile one of hydrolick jackes is remained fixed to prevent elongation of beam. Displacement Controlled Reversed Cyclic Loading with 1mm growth in lateral displacement with two cycle in every displacement is applied. The displacement computed is the average displacement of north and south of the beam. (load toward south is taken positive)

b) Analytical Work: (ABQUS FEA Modeling)

P1, P2 loads were applied uniqly disturbuted tensile to the model at the two ends of console beams, compression load is taken posetive and toward the south is posetive, P1, P2 were applied in step 3 (in step 1 prestressed forced were applied to frame and in step 2 prestress force applied to brace). Considering Experimental work of Watanabe and partners [9] the maximum P_1 load was taken 800KN which is disturbuted on consule corner beams (325x275 beam) the tension applied to simulate the load is 9N/mm^2, this load is applied by special function and has growth from 0 to 800KN by function. Figure 11 indicates the lateral load applied to the model and Figure12 showes 3D meshed model.

Lateral Load Application Function in ABAQUS Model the lateral load function is defined as a cyclic load with periodically changes from negative (tensile) to posetive (compression) and reverse, with amplitude of 0 to 800KN. The function is an "Smooth step" type which applies lateral load gradualy from 0 to maximum amplitude in specified time so it hinder the load to be applied abruptly and incorrectly [11, 12], which may lead to impact and influence the resultes. This type of loading is similar the experimental work [9].

Defining run Steps (Procedure) in ABAQUS model (Figure 13) In first and basic run step (initial step) the boundary condition which is foundation beam connection to the ground is applied to the model.

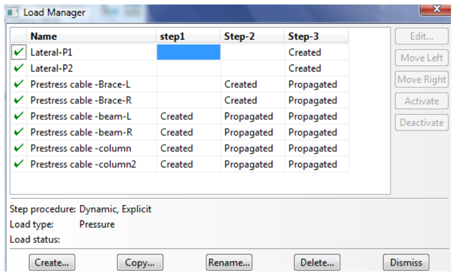

Figure 11. Lateral load applied with in ABAQUS

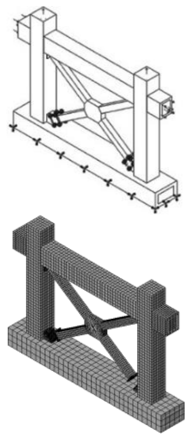

Figure 12. 3D view of meshed braced frame in ABAQUS Model

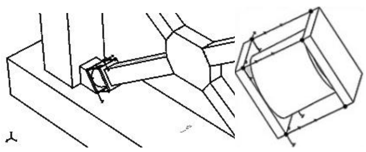

Figure 9. FSSP device Modeled in ABAQUS

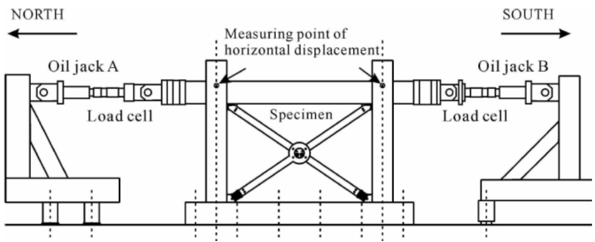

Figure10. WATANABE and partners method used for applying lateral load

TABLE 1. lateral load P1, P2 appling function; Left column of table shows Time (s) and riht Amplitude

	Time/Frequency	Amplitude
1	0	0
2	0.1	0.1
3	0.2	-0.1
4	0.3	0.3
5	0.4	-0.3
6	0.5	0.5
7	0.6	-0.5
8	0.7	0.7
9	0.8	-0.7
10	0.9	1
11	1	-1

In step 1 for prestressing beam and columns the prestress for 324KN and 300KN is applied to column and beam respectively. By running this step the results which are provided in this steps (tensile force of prestressing which is applied to entire of beam and columns) would provide next step initial conditions.by ending this step columns and beam would be prestressed, then in run step 2 the 40KN force would applied to the Leg 2 of concrete brace and this force would have distributed to entire brace, here and at the end of this step columns and beams and also braces are prestressed and RC frame is ready to resist lateral forces. Finally, in run step 3 lateral cyclic force would have applied to the model. Figures 14 to 17 indicates the run steps. Terefore, the resultes and outcomes of every step would provide next step initial conditions.

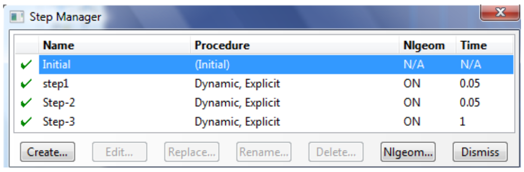

Figure 13. Run Steps in ABAQUS model

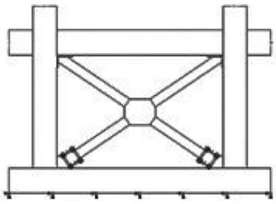

Figure 14. Initial: basic assigning boundaries (foundation to ground is assumed as fixed connection

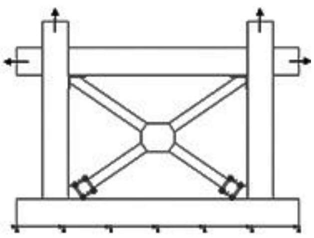

Figure 15. Run Steps, step 1 prestressed force is applied to beam and columns

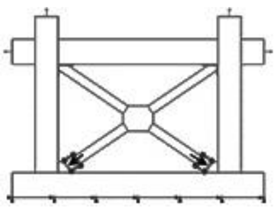

Figure 16. Run steps C) step2 prestressed force is applied to brace

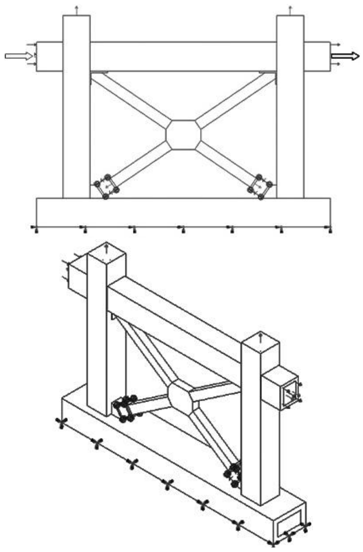

Figure 17. Run steps d) step3 lateral load is applied to Braced frame

5. STUDY THE SEISMIC BEHAVIOR OF CONCRETE BRACE AND FRAME

5. 1. NO.1 Specimen

5. 1. 1. Model Results For indicate the lateral load applied to the model at any given time,by summing up the base shears (reactin forces) provided in all the point of foundation, the lateral load could be provided. Figure 18 shows a base shear diagram for a point of foundation in model No. 1. Figure 19 indicates the total base shear (KN) in model No. 1, the lateral applied load would be base shear provided in reverse direction Figure 18.

The lateral load applied to the model is base shear load with the reverse direction.to indicate the lateral load which is applied to the model, the base shear load is provided in Figure 19 should be multiplied by -1 and Figure 22 is provided.

Total displacement of model would be provided by averaging the point is indicated in left column and the point is indicated in right column-Figures 23 and 24.

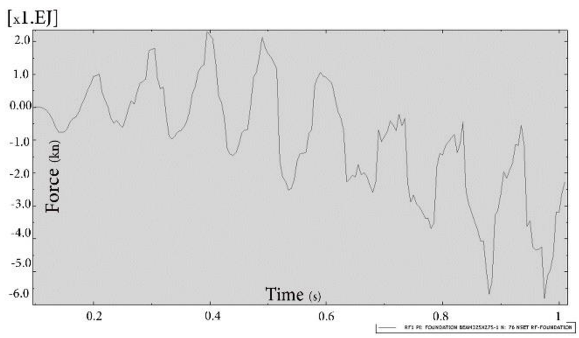

Figure 18. Base shear diagram for a point of foundation, model No.1

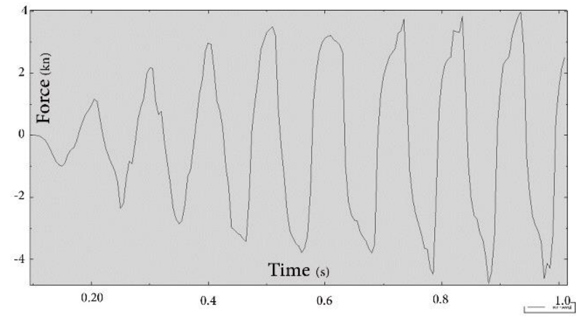

Figure 19. Total base shear(KN) in model No. 1

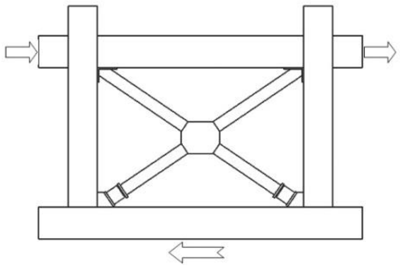

Figure 20. lateral load and base shear relation diagram

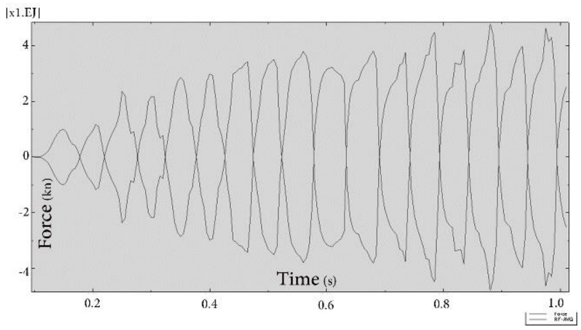

Figure 21. Comparison between lateral load-time diagram and base shear-time diagram

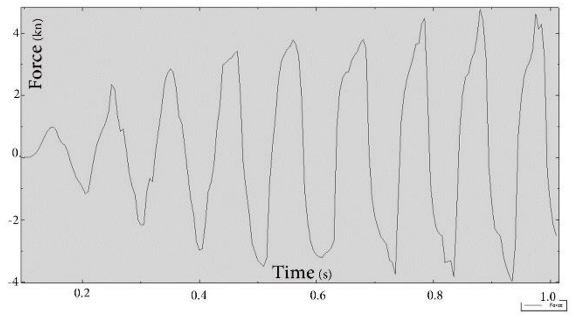

Figure 22. Lateral force(kn) – time (sec) diagram No. 1

(In the experimental work in those two point have put srain-gage-Figure 23) is showed in Figures 19 and 20.

To provide lateral force - displacement diagram, two charts should be combined. Figure 22 which indicates the lateral load applied to model trough Time and Figure 28 which indicates average lateral displacement trough Time, and elimination common factor –Time - the Figure 29 would be provided which shows lateral force-displacement. Refer to Figures 25 to 28.

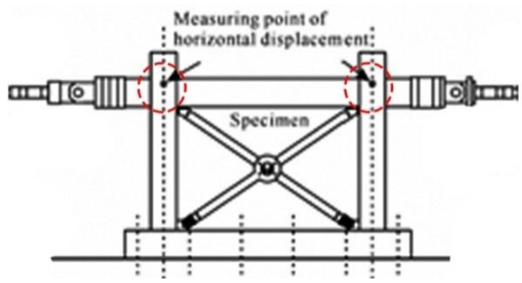

Figure 23. The point indicated the strain-gages installed In experimental work [9, 10]

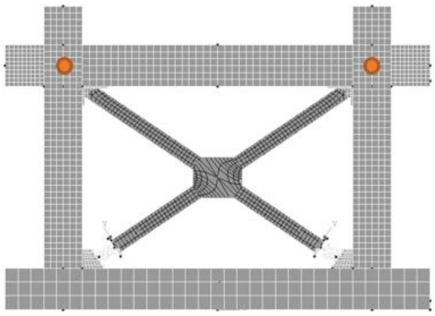

Figure 24. The points for mesuring strain in model

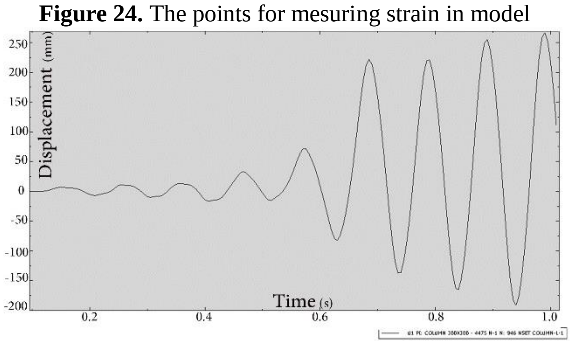

Figure 25. Lateral displacement(mm)-time(s)- Left column-No. 1

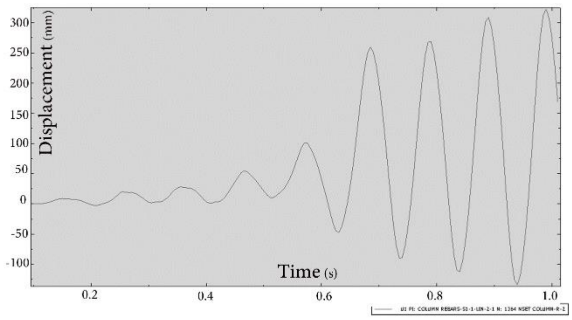

Figure 26. Lateral displacement(mm)-time(s) for Right column-No. 1

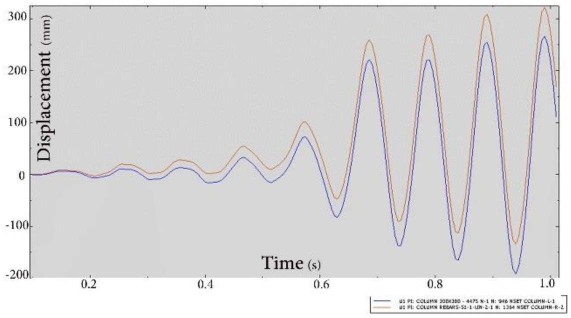

Figure 27. Lateral displacement(mm)-time(s) both left and right column in one chart for comparison

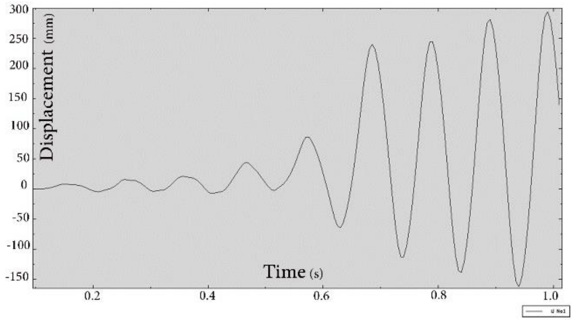

Figure 28. Average displacement which is compouted from the left and right column(mm)- Time(s) diagram

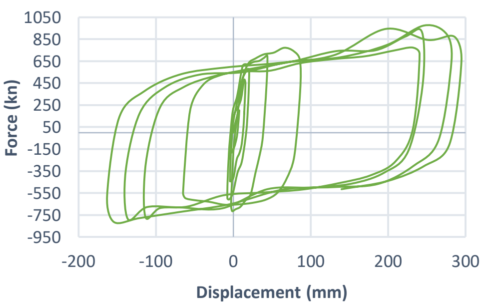

Figure 29. Lateral force (KN) - displacemet (mm) – model NO. 1

5. 1. 2. Failure Modes – Model No.1 Model No. 1 failure mode was due to buckling one of it's diagonal braces (Leg 1). Figures 30 and 31 shows failure modes which is provided by the ABAQUS, that figure indicates that the Left diagonal brace member has buckled.

Comparison between Model and Experimental Work Both experimental and analytical model No. 1 were yielded by buckling of the brace member, maximum capacity of brace No. 1 in experimental work was 397 KN in positive direction and 410 KN in negative direction (direction toward south was assumed positive).

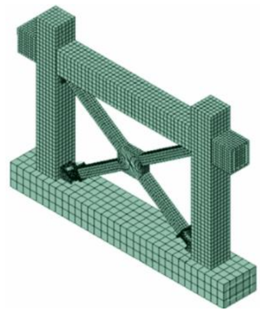

Figure 30. Braced frame befor failure

Figure 31. Failure mode of braced frame model NO .1- diagonal member buckeling

And maximum load which was carried by model No. 1 in analytical work was 975KN in positive and 812 KN in negative (Figure 32).

5. 1. 3. Comparison between Lateral Displacement of Primary Frame and Braced Frame Model No. 1

In Figure 33 lateral force-displacement diagram for primary frame and braced frame model No. 1 is provided, it is indicating that concrete brace has led to greater lateral load capacity, it showed growth from 790KN to 975Kn (23% increase) and lateral displacement has reduced from 324mm in primary frame to 294mm in braced frame. See also failure mode in Figures 31 and 34.

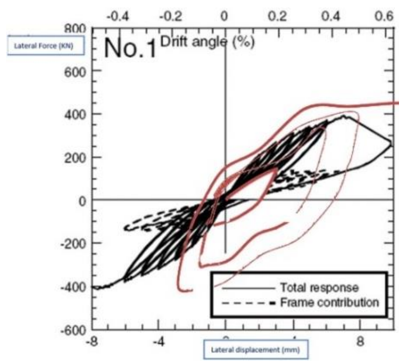

Figure 32. experimental and Analatival work resultes in model No. 1

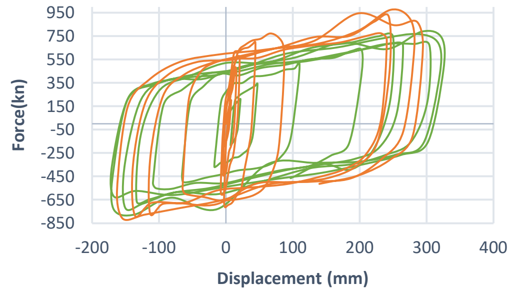

Figure 33. Force-displacement diagram model No. 1

Figure 34. Failure mode primary frame (frame is not retrofited) in shear

5. 2. NO.2 Specimen In model No. 2 all the properties are the same in model No. 1 expect: frame compression strength is assumed 25Mpa and brace section is changed to 120mm x 150 mm and the brace compression strength is assumed 64.1 MPA. Failure mode anticipated for model No. 2 due to brace section and compression strength is direct shear at the joint of beam and column.

Model No. 2 was loaded in ABAQUS due yielding and it maximum load carried by model No. 2 was 1133 KN in positive direction and 1212 KN in negative direction. Maximum displacement before failure was 20 mm.

5. 2. 2. Failure Mode Model No. 2 It is indicated in Figures 35 and 36 that model No. 2 failure mode in analytical work (ABAQUS model) was shear at the end of the column which is in match with experimental work [9].

In Figure 38 lateral force-displacement for primary frame and braced frame model No. 2 is provided, it is indicated that lateral load capacity has increased from 790KN for the primary frame has growth to 1133 KN for braced frame (43% increase) and lateral displacement of primary frame is reduced to 20mm which was 325 mm (Figures 37 and 38).

5. 3. Comparison Displacement-Time Diagrams of Primary Frame and Braced Frame Model No. 1 and Model No. 2 all three models were applied load due to failure, it is indicated in Figure 39 that model No. 1 didn't show great stiffness and it failed due

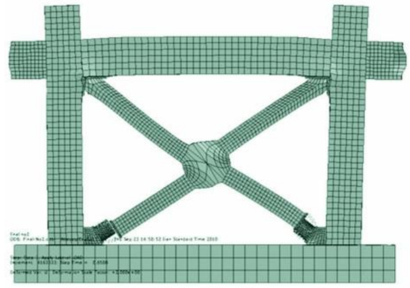

Figure 35. Failure mode model No. 2 shearat joist

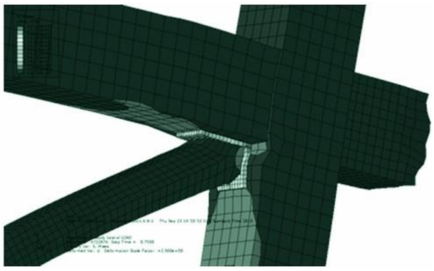

Figure 36. Local failure model No. 2

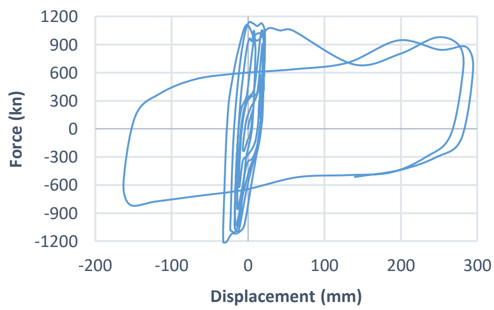

Figure 37. Lateral force – displacement model No. 2

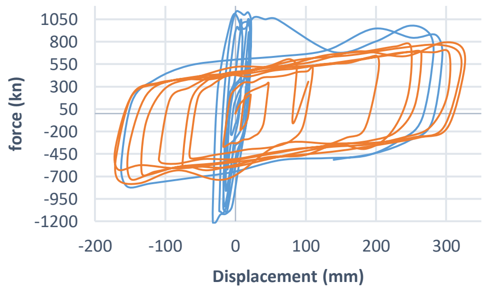

Figure 38. Laterla force-displacement primarly frame and brace frame model No. 2

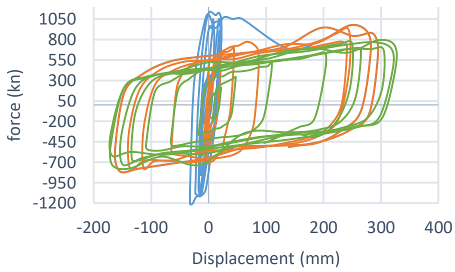

Figure 39. lateral forec-displacement of primary frame and brace model No. 1 and No. 2

to brace buckling, the slope of the lateral force-displacement (which indicate the stiffness) of that was parallel to primary frame. Model No. 2 which compression strength of that was 3 times greater than model No. 1 showed proper stiffness and lessened lateral displacements in primary frame.

Comparison of lateral Force-Time diagram of primary frame and braced frame model No. 1 and model No. 2:

All three models were applied load due to failure, chapter16 indicates that braced frame model No. 1 is effective in reducing lateral displacement before brace buckling of brace. Model No. 2 which the compression strength of brace was 4 times greater than model No. 1 showed proper stiffness and reduced lateral displacements in primary frame. Maximum lateral displacement of primary frame was 325 mm and in braced frame model No.1 was 294 mm and in model 2 is 20mm.

7. SUMMARY

1) In this research for Studying seismic behavior of "Precast Prestressed Concrete Braces" two models were created using ABAQUS FEA, the results which were provided was compared to experimental work which was obtained by WATANABE and partners.
2) In braced frame model No. 1 both models in experimental and analytical works were yielded by brace buckling, the maximum capacity in experimental work in braced frame model No. 1 was 397KN in positive and 410KN in negative direction. And maximum load was bearded by analytical model was610KN in positive and 598KN in negative direction according to Figure 33.
3) Primary frame in ABAQUS was failed due column rebar yield. The maximum lateral load capacity which was bearded by frame was 790KN in positive and 774KN in negative direction.
4) Comparison lateral Displacement-Time diagram in braced frame model No1 and No. 2 and primary frame indicated that concrete braces are proper and effective in reducing lateral displacements. (Figures 33, 35, 38, 39 and 40)
5) In Figure 33 by comparison lateral displacement of primary frame and retrofitted frame it is concluded that lateral load bearing capacity of retrofitted frame has increased from 790KN to 975KN (23% increase) and lateral displacements of primary frame is reduced from 324mm to 20mm in the retrofitted frame with brace model No. 1.
6) Braced frame model No. 2 was loaded due to failure, and it was failed by shear failure in columns. The maximum capacity of braced frame No. 2 was 904KN in positive and 843KN in negative direction, and maximum lateral load before yielding of frame was 18mm.
7) Figure 38 indicates lateral force-displacement of primary frame and braced frame No. 2, it shows that load bearing capacity of frame has increased from 790KN to 1133KN (43% increase) and lateral displacement of primary frames is reduced from 325mm to 17mm by retrofitting with brace model No. 2.
8) It is concluded from Figures 35, 38, 39 and 40, by comparison lateral force-displacement diagrams of braced frame model No. 1 and model No. 2 by primary frame- that applying Precast Prestressed Concrete Braces would add extra stiffness to frame.all three models (primary frame and braced frame model No. 1 and No. 2) were loaded due to failure, Figure 40 shows that model nomber1 did not showed much stiffness and it yielded due to brace buckling, and the slope of the lateral force-displacement of it (which indicates the stiffness) is parallel and coincide with primary frame. Braced frame model No. 2 which the brace compression strength was 4 times greater than model No. 1 added proper and effective stiffness to the frame and lateral displacements of frame were reduced from 325mm in primary frame to 17mm in model No. 2. Which was reduced by brace frame model No. 1 to 20mm.
9) Failure modes of braced frame model No. 1 and No. 2 which are showed in Figures 25 and 26, respectively. Failure compare to primary frame which is indicated in Figure 24 indicates that: primary frame was failed by shear failure in column, brace frame model No. 1 was failed due to brace buckling and braced model No. 2 failed by joint-fail. From the failure mode perspective, the analytical model and experimental work were in great conformity which indicated modeling and assumptions in ABAQUS are correctly considered. Figure 41 shows all models and their failure modes.
10) When compression strength of brace to primary frame ratio is increased, lateral load bearing of frame would increase and lateral displacements is reduced.
11) To provide proper seismic behavior, brace section and shape and properties should be considered so the brace would not fail before frame fail and could carry lateral load due to final steps and by dissipating energy the seismic behavior of frame would be increased.

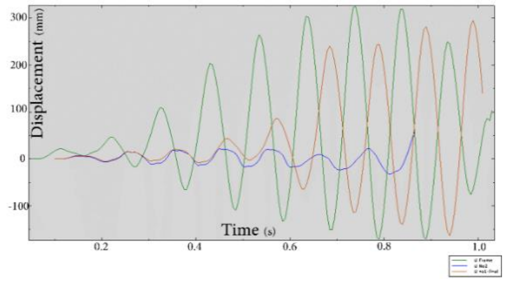

Figure 40. lateral force-dissplacement primary frame and braced frame models No. 1 and No. 2

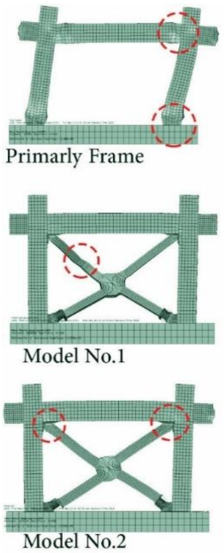

Figure 41. all models and their failure modes a)primary frame b)braced frame model No. 1 c) braced frame model No. 2

8. ACKNOWLEDGEMENT

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Seismic Retrofitting RC Structures with Precast Prestressed Concrete Braces-ABAQUS FEA Modeling

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چکیده

یک روش پیشنهادی جدید برای مقاوم سازی لرزه ای سازه های بتن آرمه به کار بردن مهاربندهای پیش تنیده پیش ساخته بتنی است که مزایای آن این است که در محل نصب با بتن تر کار نمیشود ، نصب آن آسان است و نیازی به انکر و بولت میلگرد به قاب موجود نمی‌باشد ، به همین دلیل سرعت اجرایی بالایی دارد که این خود موجب کاهش هزینه ها می شود. برای بررسی رفتار لرزه ای سازه مقاوم شده با مهاربند بتنی ، مدلی از قاب و مهاربند با نرم افزار المان محدود آباکوس (ABAQUS FEA) ساخته شد ، مقایسه قاب اولیه و قاب تقویت شده موثر بودن مهاربندها را در کاهش تغییر مکان ها نشان داد. بررسی پارامتر رده مقاومتی بتن بر رفتار مهاربند نشان داد در نمونه انتخاب شده زمانی که رده مقاومتی مهاربند کمتر از رده مقاومتی قاب موجود باشد مهاربندها سختی کمی دارند و تاثیر چندانی در کاهش جابه‌جایی ها ندارند ولی در نمونه های با نسبت رده مقاومتی بیش از 2 برابر ، مهاربند سختی زیادی به سازه اعمال می نماید و کاهش تغییر مکان های جانبی آن مشهود است.

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