



Improving The Behavior of RC Short Columns By Using Sifcon Coating and Rubber Dampers

Betonarme Kısa Kolon Davranışının Sifcon Mantolama ve Kauçuk Sönümleyici Kullanılarak İyileştirilmesi

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Abstract

In this study, improving the behavior of short column region by means of higher energy consumption and higher shear load carrying capacity is aimed. For this purpose, a special kind of concrete with high steel fiber ratio (SIFCON) is used for coating of column and placing rubber dampers around the short column region was proposed. A numerical analysis with Abaqus software was carried out. As a result, it's seen that; the SIFCON coating increased the shear force carrying capacity of short column by 2,18 times when compared with non-retrofitted specimen, whereas additional rubber dampers around the short column region increased the total load carried by 4 times. Also, the energy dissipation of the region increased by 2,02 to 2,82 times when compared with non-retrofitted situation. As a result, it was seen that, with a practical approach it is possible to improve the behavior of short columns.

Anahtar Kelimeler

“Short column, SIFCON, Rubber dampers, Abaqus, Finite element method”

ÖZ

Bu çalışmada, kısa kolon bölgesinin davranışının daha yüksek enerji tüketimi ve daha yüksek kesme kuvveti taşıma kapasitesi açısından iyileştirilmesi amaçlanmaktadır. Bu amaçla, kolon mantolanması için yüksek çelik lif oranına sahip özel bir beton (SIFCON) kullanılmış ve kısa kolon bölgesinin çevresine kauçuk sönümleyiciler yerleştirilmesi önerilmiştir. Abaqus programı ile nümerik analiz yapılmıştır. Sonuç olarak görülmüştür ki; SIFCON mantolaması, güçlendirilmemiş numuneye kıyasla kısa kolonun kesme kuvveti taşıma kapasitesini 2,18 kat arttırırken, kısa kolon bölgesi etrafında ilave kauçuk sönümleyici kullanılırsa, kesme kuvveti kapasitesi güçlendirilmemiş kolona nazaran 4 kat arttırılmıştır. Ayrıca, bölgenin enerji tüketimi, güçlendirme yapılmayan duruma göre 2,02 ila 2,82 katına çıkmıştır. Sonuç olarak, pratik bir yaklaşımla, kısa kolonların davranışını iyileştirmenin mümkün olduğu görülmüştür.

Key Words

“Kısa Kolon, SIFCON, Kauçuk sönümleyici, Abaqus, Sonlu elemanlar metodu”

1. Introduction

Strong earthquakes cause big casualties around the globe and in Türkiye. Recent earthquakes in Kahramanmaraş region showed that existing reinforced concrete (RC) building stock is risky and conventional or new methods must be used for the seismic retrofit of structures immediately. In Türkiye, low concrete strength, insufficient usage of confinement and longitudinal rebars, soft story and weak story irregularities can be counted as the common reasons for the non ductile and insufficient behavior of buildings during strong earthquakes. Additionally, short column behavior is one of the common mistakes in many buildings, especially in buildings where a basement story which contains RC walls exists with a long window from column to column. It's observed in the buildings where infill walls were constructed in such a way that their height is not as high as the column. The infill walls restrict the lateral displacement of the columns along their height. Also in some buildings, in the columns in staircases short column mistakes exist. In Figure 1, an example of a short column behavior is seen. The short columns are subjected to big shear forces and they must be designed according to it. However, short column behavior is generally occurs due to the wrong application in the construction site. In capacity design method, when plastic hinges occurs at column ends, the shear force acting to the column can be calculated by taking the summation of the plastic moments at column ends and dividing them by column height. Due to the wrong application in construction sites, the bigger shear forces than expected ones causes a non ductile failure in short columns. The short column fails due to shear before it reaches to its ultimate capacity.



Figure 1. An Example of a Short Column

Ductility is a key concept in design of RC structures. Traditionally, the dynamic behavior of RC structures under earthquakes is analysed by constructing the mass, stiffness, and damping matrices of the structures and solving the equation of motion. Computer softwares use numerical methods to solve the equation of motion. However some attempts were made to analyse the same problem by means of an energy conservation equation. These methods were called as energy based design. In a previous study, concepts of energy based design were explained and it's said that if equation of motion based on Newton laws was transformed to an energy equation, it could be written as follows (Merter and Uçar, 2016):

$$E_K + E_D + [E_{SE} + E_P] = E_I \quad (1)$$

Here E_K indicates the kinetic energy, E_D indicates the energy consumed by damping, E_{SE} indicates the energy consumed by linear behavior, E_P indicates the energy consumed by nonlinear behavior of structure and E_I indicates the earthquake input energy. In equation 1, kinetic energy and linear strain energy can be neglected and only plastic energy and damping energy can be considered. That is why seismic dampers are used as an alternative seismic retrofit method for the purpose of an increase in damping energy and a decrease in plastic energy of structures. Thinking the problem by means of an energy conservation equation reveals the importance of ductility once again. Short column mistake which restricts the ductility of structures must be analysed, and behavior of short column region must be improved.

In a previous study, the effect of existing short columns to the behavior of structures was examined by performing nonlinear time history analyzes. 4 and 7 story structures were modelled three dimensionally and 12 ground motion records were used for the analyzes. All of the columns at the two of the outer axis of structures were assumed to be short columns and these structures were compared with structures without any short columns. The structures were modelled by using plastic hinge approach. During the modelling of columns, moment plastic hinges, shear hinges, and axial load hinges were assigned to the column ends in Sap2000 software. As a result it was concluded that short columns causes around 10-15 percent increase in base shear, 10-30 percent increase in the lateral relative drifts of stories in structures with short columns. Also the structures without short columns had 27-45 percent more lateral roof displacement ability which indicates more ductile behavior. In the structures with short columns in the first story, 40 to 60 percent of columns had a severe damage and collapsed, however in structures without short columns, collapsed column ratio in first story was around 8 percent. In this study it was mentioned the importance of modelling the shear hinge in columns accurately to reflect the short column behavior. Also, members were assumed to be collapsed when they reached their shear strength and no ductility was considered in shear hinge behavior (Meral, 2019).

In another study, the behavior of short column specimens were examined experimentally and numerically. For that purpose, short column specimens with 80cm-1m height were tested. Also, square slabs with 90cm width were considered at the top and bottom of short columns to reflect the behavior of a real short column. To improve the behavior, additional diagonal rebars and an arrangement for rebars were proposed. It was seen that the proposed diagonal rebars increased the shear strength of specimens and they could

approach to flexural type of behavior. Also the proposed rebars increased the ductility. In this study the numerical analysis showed good agreement with the experimental results (Dirikligil, 2014).

Later the study mentioned in previous paragraph was extended by using CFRP wraps for strengthening of short columns. In the experimental study where specimens were subjected to hysteretic lateral loading under constant axial load, specimens with additional diagonal rebars inside columns and specimens with CRFP wrapping showed superior behaviour when compared with reference specimens which were constructed according to the regulations (Dirikligil and Atas, 2019).

In a study where SIFCON concrete (An easily workable type of concrete with high amount of cement, high amount of steel fibers and low water/cement ratio) was used to strengthen short columns and improve the behavior of RC frames with different kind of infill wall arrangements, the specimens were examined experimentally. In most of the specimens infill walls were constructed in a way to cause a short column behavior on purpose. It was concluded that specimens which were strengthened by SIFCON panels had 40% to 75% more strength when compared with reference specimen. SIFCON panel strengthening increased the energy consumption of the frames. It was emphasized that one of the advantages of using SIFCON panels was allowing a retrofit process without changing the architecture of buildings (Kayacik et al., 2023).

In another study, Abaqus software is used to investigate the behavior of short columns to validate the results of experiments done previously. Under constant axial load, short column specimens which include beams at top and bottom parts were modelled and subjected to a unidirectional hysteretic loading to validate the results of previous experiments. After the analysis the shear force-lateral displacement curves were determined and compared with experimental results. In unidirectionally loaded specimens the numerical results showed good agreement with the experimental results. Then the study was extended to analyse the behavior in bi-directional loading. For that purpose, the effect of loading from both directions were assumed to be applied simultaneously or sequentially. It was concluded that sequentially loading decreased the shear capacity of columns more significantly. Also the stresses were analyzed in rebars and in concrete. It was concluded that concrete damaged plasticity model (which is available inside Abaqus) is an appropriate model to reflect the behavior of concrete in shear (Alraquad et al., 2022).

In this study, improving the behavior of short column region was aimed. For that purpose, the effect of SIFCON coating to a short column and the effect of adding rubbers to increase the energy consumption, was numerically analyzed by using Abaqus software. Under constant axial loading, shear force- displacement graphs were obtained. Shear force- displacement graphs are important to reflect the behavior of the column as indicated in the previous study where shear hinge was used at column ends to model short column behavior (Meral, 2019). So if the combined behavior of SIFCON coating and placement of rubber dampers are understood, shear hinge properties can be determined properly for a seismic retrofit process by using the proposed method.

2. Materials and Method

2.1. Modelling concrete

In literature some theories and models were proposed to predict the materials' plastic behaviors under multidirectional stresses. The stresses which the material is subjected can be assumed as an imaginary combination of hydrostatic part and deviatoric part. The proposed theories consider hydrostatic or deviatoric part of stresses or all of them to predict the behavior. Tresca theory considers shear stresses are responsible for the nonlinear behavior of the material. Von Misses theory considers that hydrostatic part of stress situation can be neglected, because it's assumed that only deviatoric part is responsible for the plastic deformation of material. Differently than Von Misses theory, Drucker-Prager theory considers the effect of hydrostatic part of the stress situation additionally to the deviatoric part. In Abaqus software, Concrete Damaged Plasticity (CDP) model is available to model concrete. CDP model is a modification of Drucker - Prager model. As seen in Figure 2, (Santos et al.,2017) Kc coefficient determines the modification. In CDP model Kc coefficient is assumed to be 2/3, but in Drucker Prager model it's assumed to be 1.

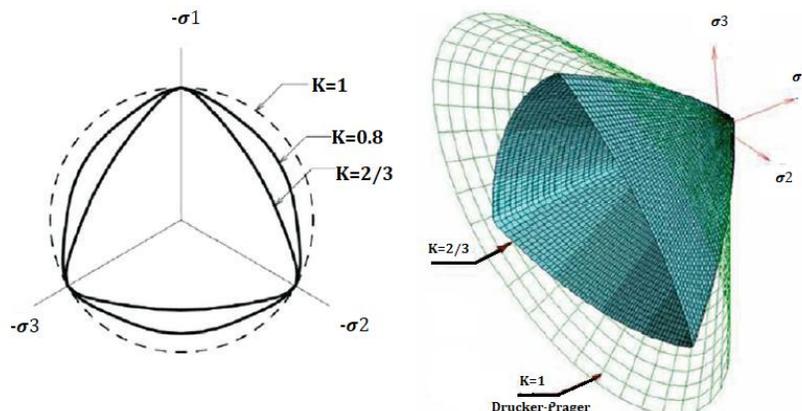


Figure 2. CDP Model (Santos et al., 2017)

In Abaqus, the compressive stress and corresponding strain of concrete is determined as shown in Figure 3 (Obadiat, 2011). In Figure 3, d_c coefficient is used to take into account the effects that changes plasticity of concrete in compression. In Abaqus, plastic strain versus corresponding stress values are used. The stress- strain relationships of the concrete were taken from a previous study where a slide canyon bridge in California, USA was considered for strenghtening (Mosallam et al., 2022). A numerical analysis was performed in that study by using Abaqus. A concrete with a compressive strength of 17,5MPa was used to mimic the behavior of the real bridge. Modulus of elasticity of concrete for frame was taken as 19662MPa. The dilation angle was taken as 40 degrees for concrete in the previous study to represent bridge’s concrete. Eccentricity value which defines the ratio of concrete’s tensile strength to concrete’s compressive strength was taken as 0,1. In CDP model, one of the other required value is the f_{bo}/f_{co} ratio which was assumed as 1,14. f_{bo} defines the strength of concrete in bi- directional loading whereas f_{co} defines the strength of concrete in uni-directional loading. The tensile strength of concrete was taken as 2,20MPa. (Mosallam et al., 2022). In Abaqus, cubic specimen results are implemented to the software for the strength of concrete. 17,5 MPa cubical strength value is considered to represent the risky building stock of Türkiye where short column mistake exists especially in old buildings constructed before 1999. The properties of concrete for CDP Model, compressive stress and strains in inelastic region, tensile stress and strains in inelastic region can be seen in Table1, Table 2 and Table 3 respectively.

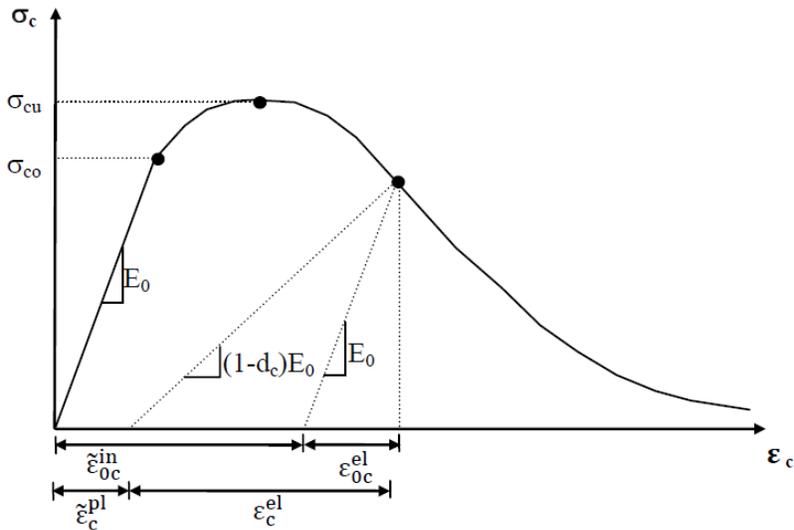


Figure 3. Compressive Stress-Strain Relations of Concrete (Obadiat, 2011)

Table 1. Properties of Concrete for CDP Model (Mosallam et al., 2022)

Parameter	Value
Modulus of Elasticity	19662MPa
Onset Yielding Stress	15.20MPa
Crushing Stress	17.5MPa
Tensile Ultimate Stress	2.20MPa
Poisson's ratio	0.18
Dilation Angle	40 degrees
Eccentricity	0.1
f_{bo}/f_{co}	1.14
Viscosity Parameter	0.5

Table 2. Compressive Stress and Strain of Concrete in CDP Model (Mosallam et al., 2022)

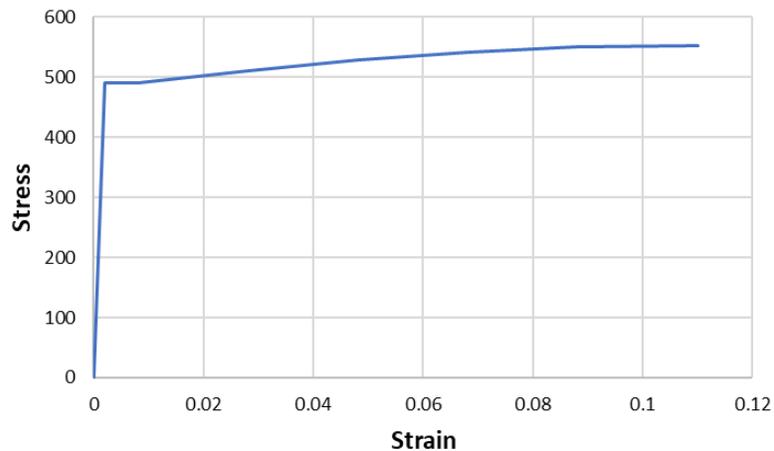
Yield Stress (MPa)	Inelastic Strain
15.2	0
17.5	0.000638796
16.5	0.00156087
13.8	0.00257523
11.4	0.00357331
9.3	0.0045
7.9	0.00545631

Table 3. Tensile Stress and Strain of Concrete in CDP Model (Mosallam et al., 2022)

Yield Stress (MPa)	Inelastic Strain
2.2	0
1.8	0.000132818
1.4	0.000367127
1.2	0.000482791
1	0.000598454
0.7	0.000925081
0.5	0.00114291
0.3	0.00515414

2.2. Modelling rebars

A steel rebar with the commercial name of B420C was used as the longitudinal and confinement rebars inside the column. The stress strain properties of the steel rebar were taken from a previous study where the rebar properties based on the test results available in the factory was used. In that study the steel's stress-strain curve was determined by using the procedure explained in Turkish seismic code 2018 for performing a nonlinear analysis of a structure. The stress-strain curve is seen in Figure 4 (Koman, 2021). In Abaqus modelling for confinement, rebars with 8mm diameter is used. For the modelling of longitudinal rebars in short column and beams, rebars with 16mm diameter was used.

**Figure 4.** Stress Strain Relationships of Steel Rebar (Koman, 2021)

2.3. Modelling SIFCON

SIFCON is a term for shortening slurry infiltrated fiber concrete. To produce SIFCON, high amount of steel fibers (5% to 30%) are replaced in the form and the cement matrix which is consisted of fine aggregates and high amount of cement is applied. SIFCON has high ductility, high toughness and it exhibits minimal strength degradation (Wood, 2000). This is not a surprising result because in normal concrete, the coarse aggregate/cement matrix transition zone is the weakest region of concrete. In this region water/cement ratio is higher than the rest of the cement matrix resulting in lower strength. The concrete exhibits a nonlinear stress- strain curve despite the components of concrete (cement matrix and coarse aggregates) exhibits nearly a linear behavior under stresses due to the existence of the transition region between coarse aggregate and cement matrix (Mehta and Monterio., 2006). In SIFCON, eliminating the transition zone by not using any coarse aggregate and usage of high cement and steel fiber ratio allows a ductile behavior. In old buildings during retrofitting process, rebar placement for coating of existing members requires labor. Building owners and residents do not want to allow time consuming retrofitting processes because of the neediness of moving away during the process. To overcome this difficulty practical solutions with minimum workmanship is required. For that purpose SIFCON is selected for the coating of existing short column.

In literature, for considering SIFCON’s compressive and tensile strength, models were proposed. In the model explained in a previous study, for compressive behavior, an ascending branch and a descending branch for the stress strain curve for SIFCON is defined. This assumption is based on the high ductility and toughness of SIFCON material. In the ascending branch, the compressive strength of the material can be defined as follows (Wood, 2000):

$$\sigma_c = \sigma_{max} [1 - (1 - \epsilon/\epsilon_{max})^A] \tag{2}$$

$$A = E_0 (\epsilon_{max}/\sigma_{max}) \tag{3}$$

Here, σ_{max} indicates the strength of the SIFCON material in compression, σ_c indicates the corresponding stress at strain ϵ , ϵ_{max} indicates the strain occurring at σ_{max} , E_0 is the modulus elasticity of SIFCON (Wood,2000). For the descending branch of the material, the following equation was proposed in the same study (Wood, 2000):

$$\sigma_c = (\sigma_{max} - \sigma_{plat}).e. [-b\epsilon^m \left(\frac{\epsilon}{\epsilon_{max}} - 1\right)^m] \tag{4}$$

In equation 4, b and m parameters must be defined. b parameter is dependent on m and it’s explained in equation 5 in the same study (Wood, 2000)

$$b = (m-1)/[m(\epsilon_{infl}-\epsilon_{max})] \tag{5}$$

In equation 5 ϵ_{infl} is the strain at which compression curve reverses curvature. m value in equation 5 can be written as shown in equation 6. Here σ_{infl} is the stress at which compression curve reverses curvature and σ_{plat} is the constant stress reached at the end of a compression test. (Wood, 2000) :

$$m = (1 + \ln [(\sigma_{infl} - \sigma_{plat})/(\sigma_{max} - \sigma_{plat})])^{-1} \tag{6}$$

Figure 5 (Homrich and Naaman,1987) explains the meaning of the terms given in equations.

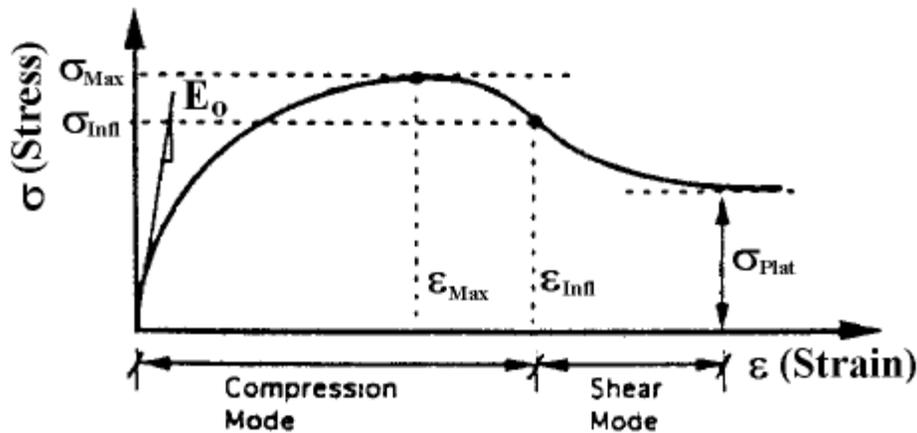


Figure 5. SIFCON Compression Stress-Strain Curve Model (Homrich and Naaman,1987)

The SIFCON material used in this study for the coating of short column has a compressive strength of 44.13 MPa. The properties of the material were taken from a past study where the experimental tests were carried out with SIFCON specimens with different steel

fiber ratios (Prathima and Babu, 2016). Specimen with randomly distributed steel fibers with a ratio of 15% was selected. The modulus elasticity of the SIFCON material was measured as 7062,5MPa, the strain corresponding to peak stress was measured as 0,0049 in the previous study. The maximum strain can be read as 0,007 from the graph given in the study. It's said that, SIFCON material's behavior is similar to mortars in compression (Prathima and Babu, 2016). Equations (2-6) were applied to compare the behavior proposed by the model by the real stress strain curve given in the previous study. As a conclusion it's seen that ascending branch can be modelled accurately by equations 2 and 3, however for the modelling of descending branch exact value for σ_{plat} was needed. This value was not given in the experimental study, because the stress strain curve assumed to be finished around ϵ_{infl} (Prathima and Babu, 2016). So the values for descending branch was taken from real graph until ϵ_{infl} which is accepted as 0.0065 and the rest is determined by equation 4 by accepting σ_{plat} as 22MPa. As a result the stress strain curve for SIFCON in compression is determined as follows:

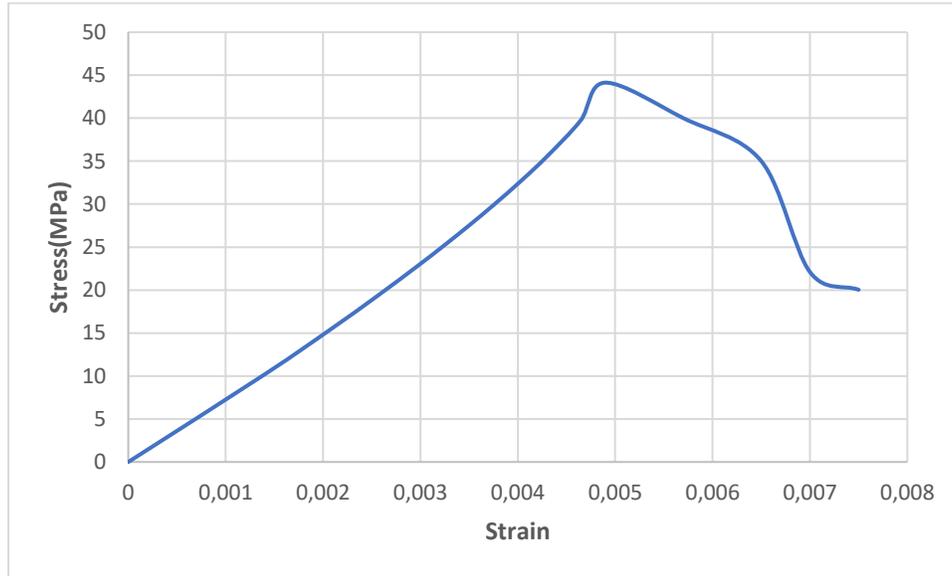


Figure 6. The Compressive Stress- Strain Curve of SIFCON Used for Coating of Short Columns

For the tensile behavior of SIFCON, a model which describes the behavior by separating it to an ascending branch and a descending branch was proposed in the past study. The ascending branch of the model is as follows:

$$\sigma_t = \sigma_{tmax} [1 - (1 - \epsilon/\epsilon_{tmax})^D] \tag{7}$$

Here, D coefficient and ϵ_{tmax} (maximum strain in tension) are dependent on initial modulus elasticity of SIFCON in tension, steel fiber ratio, maximum tension stress of SIFCON. The details can be seen in the previous study (Wood, 2000). Also a descending branch was proposed by researchers, however according to a typical stress-strain curve of SIFCON given in the same study after reaching maximum stress, the curve can be accepted as a plateau (Wood, 2000). The initial modulus elasticity of SIFCON in tension is assumed to be the half of the compressive modulus of elasticity, and strain corresponding to maximum tensile stress is taken as 0,013 based on an experimental result on the previous study (Wood, 2000). A descending branch was not defined for the tensile behavior. The stress strain relationship of SIFCON in tension which is defined by Equation 7 can be seen in Figure 7.

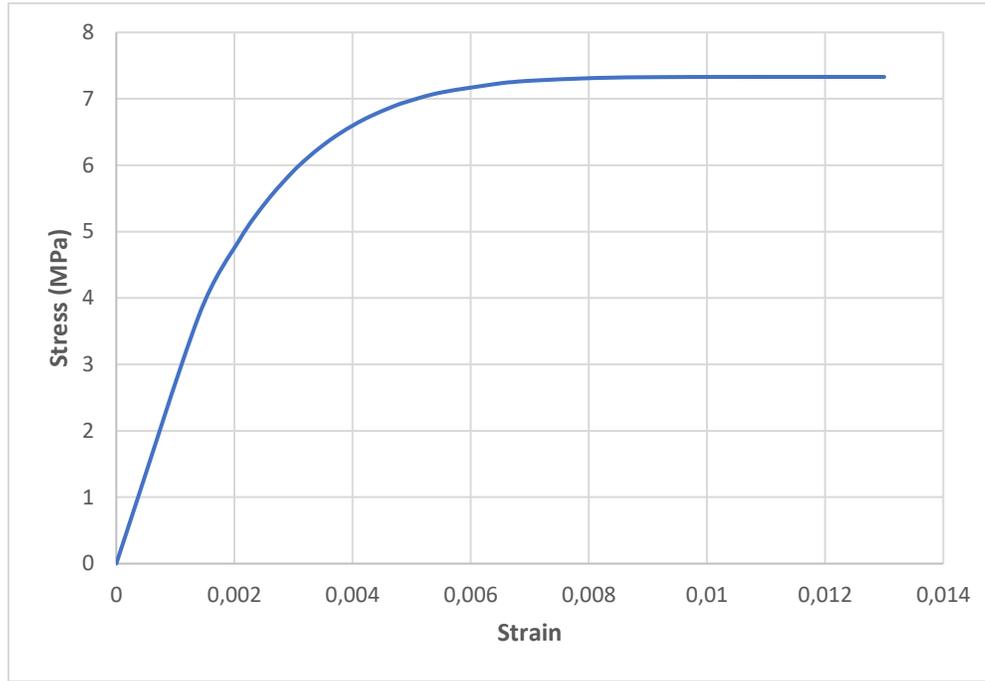


Figure 7. The tensile stress- strain curve of SIFCON

2.4. Modelling rubber

In this study, also the placement of rubber dampers were considered to increase the energy dissipation in short column region. Because as indicated by equation 1, earthquake input energy must be consumed by the structure before the collapse. Rubber and rubber like materials have a different stress- strain curve than the metals. The stress curve has an ascending branch after some yielding. In hyperelastic material modelling, stress strain relationships are derived from the strain energy function. The strain energy is equal to the area under stress strain curve of materials. By using this strain energy, in literature some models were proposed. These models define the hyperelastic behavior. However, rubber material also has time dependent deformations, in other words it has a viscoelastic behavior. To consider both kind of behavior, in Abaqus, hyperelastic and viscoelastic behavior is defined at the same time. In hyperelastic models, the strain energy function has the following general form (Jakel, 2010):

$$W = \sum C_{ij} (I_1 - 3)(I_1 - 3)^i (I_2 - 3)^j + \sum \frac{1}{D_k} (J - 1)^{2k} \quad (8)$$

Here, W indicates the strain energy, I and J values are the invariants of stress and deviatoric stress tensor, C and D are coefficients related with the material properties which must be defined. In literature, Mooney Rivlin, Neo-Hookean, Yeoh, Ogden, Polynomial models are different modifications of the general form expressed in equation 8 (Jakel, 2010). In a previous study to model rubber door stopper by Abaqus, Ogden model is used for the hyperelastic part of behavior (Erkek, 2016). Ogden formulation describes the strain energy by using the elongation of material in three directions. In uniaxial tensile test, the ratio of final length of material to the initial length of material can be written and it's showed by symbol of λ_1 . By using same approach, for a complex stress state, λ values for three directions are written. Also it's possible to write the stress invariants (I) in terms of λ values. The Ogden formulation is stated in the following form to describe the strain energy function (Ogden, 1972):

$$W(\lambda_1, \lambda_2, \lambda_3) = \sum_{r=0}^{N=\infty} \frac{u_r}{\alpha_r} (\lambda_1^{\alpha_r} + \lambda_2^{\alpha_r} + \lambda_3^{\alpha_r} - 3) + \sum_{k=1}^N \frac{u_r}{\alpha_r D_k} (J - 1)^{2k} \quad (9)$$

In equation 9, α_r and u_r are coefficients which must be determined experimentally. For defining viscoelastic part of the behavior, shear test data can be used in Abaqus software. Also viscoelastic behavior is defined based on experimental results of shear test and implementing the experimental results directly into Abaqus software. The Ogden formula coefficients were taken in Abaqus as follows: mu1: 1,21391365, alpha1: 1,68602945, D1:0. The details of Ogden formulation is explained in the previous study (Erkek, 2016). The same rubber material is used in this study for short column region. However when defining the hyperelastic behavior in Abaqus, in Ogden formulation a default value for D1 is used by the software automatically during the analysis. Because if D1 coefficient is equal to poisson ratio of material is 0.5 and material is incompressible. However, as indicated in Abaqus manual, if explicit analysis is performed, software assumes a compressible behavior with poisson's ratio of 0.475 (Abaqus Manual).

2.5. Modelling the interaction between rubber and SIFCON

In the third model, rubber layers exist between SIFCON layers as seen in Figure 10 and Figure 11. The interaction between polyurethane rubber layer and SIFCON layers must be defined in Abaqus software. In practice there are polyurethane injection materials behaving as binders between materials. Such kind of polyurethane binders are applied as fluid form and gains strength afterwards acting as rubbers. The interaction of polyurethane binders and materials are similar to the interaction between mortar and brick materials. The modelling approach is similar to the detailed micro modelling of masonry structures. Such kind of approach is used in a previous study (Koman, 2021).

In Abaqus surface based cohesive behavior can be used for modelling the interaction between binders and materials in detailed micro modelling. Using the surface-based cohesive behavior fracture separation model, a simplified method for modeling interaction zone with negligibly small interfacial thickness is provided. Surface-based cohesive behavior formulas are very similar to the formulas used for cohesive elements used with traction separation behavior. Traction separation laws are used to describe the behavior of the connection in mode1, mode2, mode3 failure modes. In other words, it is used to describe collapse behavior in tension and shear situations. At first, the connection behaves linearly and K_{nn} , K_{ss} , K_{tt} are the stiffnesses of the connection. However, after the maximum stress value that initiates separation, the plastic behavior of the joint interfaces begins (Abaqus Manual). The behavior can be seen in Figure 8.

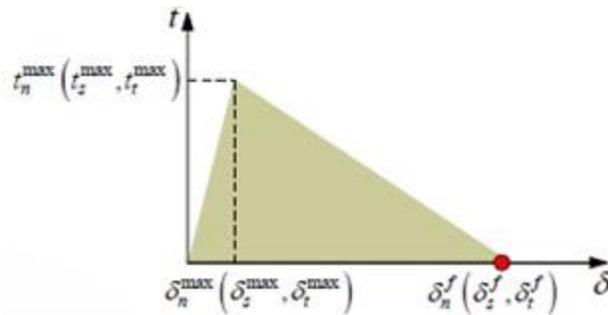


Figure 8. Traction Separation Laws (Abaqus Manual)

In Figure 8, t_n^{\max} , t_s^{\max} , t_t^{\max} are the maximum contact stresses, δ_n^{\max} , δ_s^{\max} , δ_t^{\max} are contact separations corresponding to maximum stresses and δ_n^f , δ_s^f , δ_t^f are the separations at failure. The behavior of elastic part can be defined by using the strengths of joint in normal and shear modes (the software assumes shear mode can be different in perpendicular directions, but it's assumed same). Maximum nominal stress criterion is assumed in software. That means if stresses exceed the strength of joint in normal or shear modes plastic behavior of joint will start. The joint strength was assumed as 1MPa in normal and shear modes based on the experiments of a previous study where polyurethane joint was compared with mortar joint (Viskovic et al. 2017). The fracture energies of the joint are required in Abaqus for defining plastic part of the behavior (Damage evolution in Abaqus). For that purpose, fracture energies (area under the graph of Figure 8) for normal and shear modes must be implemented into the software. Based on the experiments of a previous study where mortar binder and polyurethane binder were compared in terms of joint fracture energies (Viskovic et al. 2017), the fracture energies of joint were assumed as 63.33 Joules (Nm) for normal mode failure and 524.66 Joules for shear mode failure. This equals 4.22 N/mm for normal mode and 10.93N/mm for shear mode. The mixed mode behavior was taken into account by applying the Benzeggagh-Kenane rule in Abaqus. Finally, to describe the behaviour if the joint fails completely, a Mohr Coulomb friction behavior was assumed in the software with a friction coefficient of 0.66. This value was chosen based on the friction experiments for brick wall materials from a past study (Koman, 2021).

2.6. Model and method

Three models were constructed in Abaqus for the analysis. In the first model, 40 cm x 40 cm sized short column with a height of 60 cm was modelled. At the top and bottom of the column, beams with 2meter length and 60cm x 60cm cross sections were constructed to reflect the short column behavior. The beams and columns were constructed by using a type of concrete with 17,5MPa cubical strength. The column has 8 ϕ 16 longitudinal rebars whereas beams have 10 ϕ 16 longitudinal rebars distributed equally to top and bottom regions. The stirr-ups were arranged as ϕ 8/10cm in beams, whereas ϕ 8/15cm is used inside the short column to represent the risky building stock. 1MPa constant pressure is assumed acting to the surface of the top beam to represent vertical loading. This value is nearly equal to half of concrete characteristic strength times column cross sectional area ($0.5 \times A_c \times f_{ck}$). The base surface of the model is assumed as fixed support. As a finite element, C3D8R elements were selected for concrete. C3D8R element is an 8 noded, three dimensional element with reduced integration. For rebars, a 2 noded linear beam element called B31 was used. Rebars are embedded in column in the software. This option in software indicates that the two materials behave as a reinforced concrete cross section. A hysteretic loading which reaches 20mm maximum displacement in lateral direction is applied to the top beam. For one cycle of movement the loading time was 8 seconds. An explicit dynamic analysis is applied to the column. In explicit analysis, central difference method is used to solve equation of motion of the system matrix. In the central difference method, the stiffness, mass, and damping matrices are not reconstructed at each step, and displacements at step I+1 are found using displacements at step I and I-1.

For this reason, maybe thousands of steps are required but big computational power is not required. Computational power is often used to find element internal forces (Demir, 2012). The vertical loading and boundary conditions of the first model can be seen in Figure 9. The base was assumed as encastre support. A displacement- controlled lateral loading loading was applied. Same conditions are used in the other models.

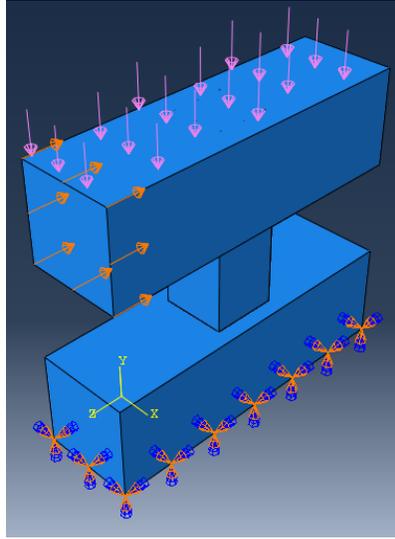


Figure 9. The Loading and Boundary Conditions of Model in Abaqus

In the second model, the short column was coated by using SIFCON layer. The SIFCON layer had a thickness of 10cm in inplane direction, 5cm thickness in out of plane direction of loading. In Abaqus, “Tie” means restricting the relative displacement and rotation of nodes at the tied surfaces according to each other and make the tied members work together. The beams and short column were tied to each other. So they can be thought as if they were molded together during concrete pouring. Also the SIFCON layer and short column cross section are tied together to make them work together (perfect anchorage is assumed in retrofitting process). In the third model, additionally to SIFCON coating, 4 rubber layers with a height of 40cm is replaced around short column between 50cm length SIFCON layers which are attached to the beams. Surface based cohesive behavior for the interaction between rubber layers and SIFCON panels are used in the model as explained in section 2.5. The shear deformation of the rubber was used for increasing the energy consumption. In these models all of the materials were modelled by using C3D8R elements except rebars. 25mm element size was chosen for concrete elements for a precise analysis. For rebars 50mm element size was chosen. In SIFCON layer mesh size was chosen as 15mm. The reinforcement details of the model 3 (reinforcement of RC part is same in all of the models) can be seen in Figure 11, and 3D Abaqus models showing finite element mesh of the system can be seen in Figure 10.

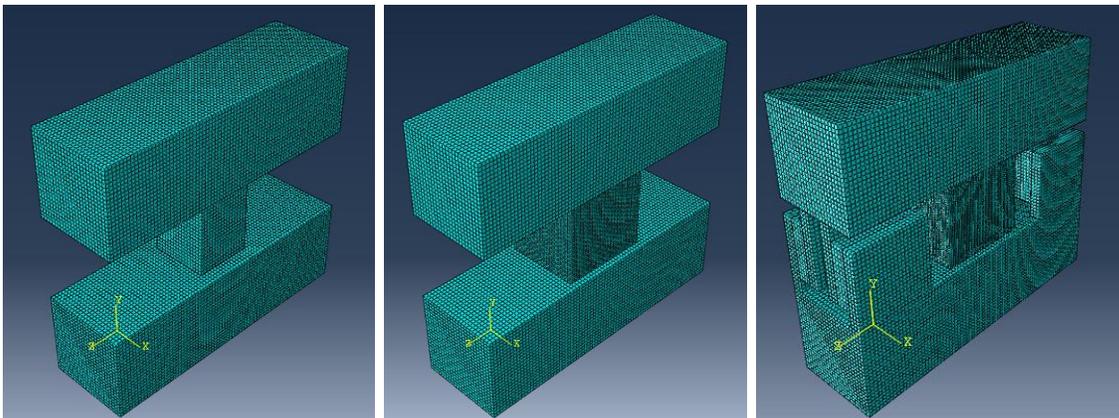


Figure 10. (a) Short Column; (b) Short Column with SIFCON Coating; (c) Short Column with SIFCON Coating and Rubber Dampers

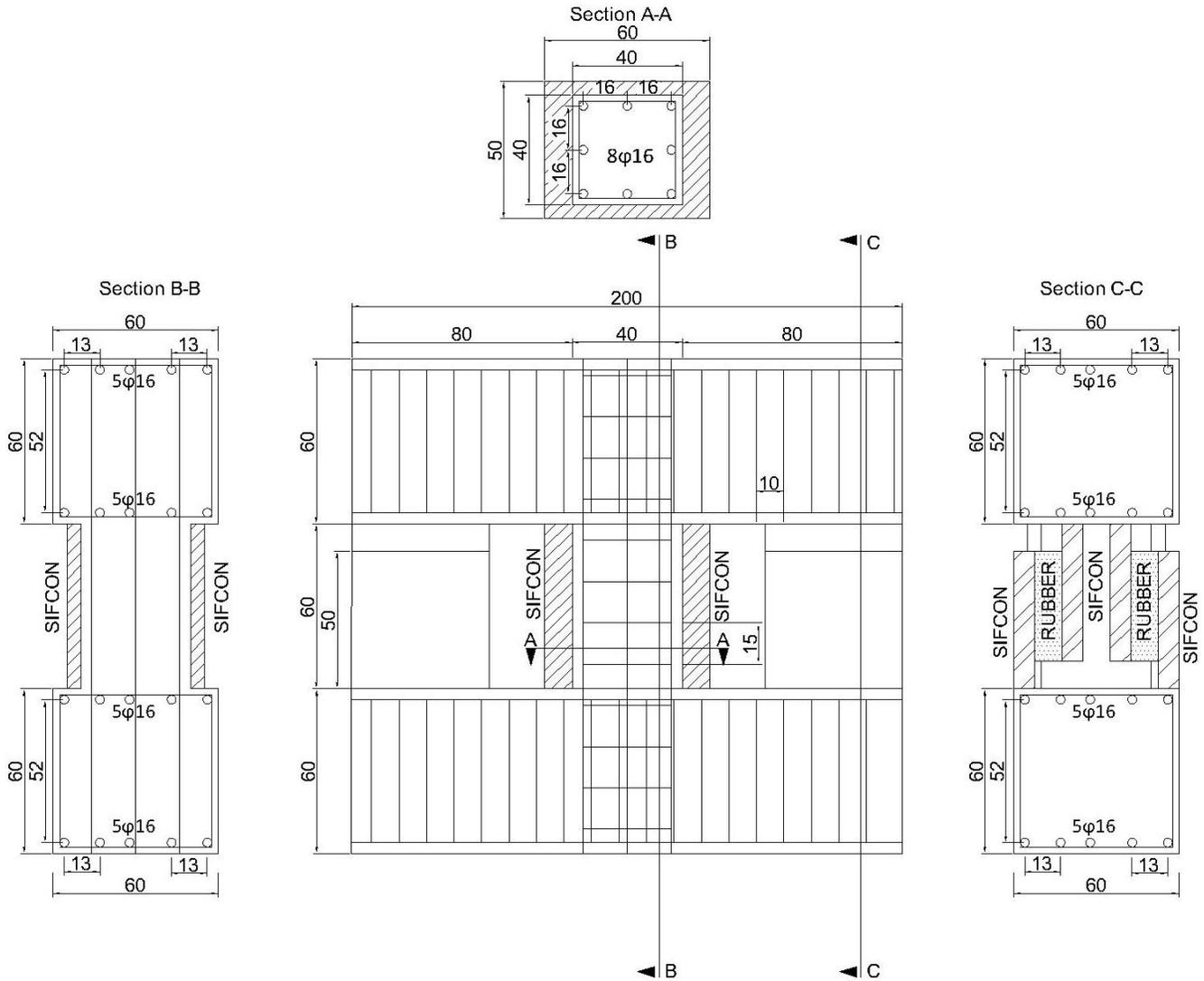


Figure 11. The Detailed Drawing of Model 3 (Length Units are in cm)

3. Results and Discussion

3.1 Hysteretic behavior and load displacement graphs of models

After the analysis, shear force-displacement graphs were obtained for each assembly. As indicated in a previous study (Meral, 2019), to model short columns, shear hinges can be used additionally to axial force hinges and moment hinges in short column region. However in the previous study, for shear hinges no ductility was determined, instead the hinges were assumed to be collapsed if the shear force reaches to the capacity of the member (Meral,2019). The shear behavior is very important to determine the behavior of short columns. In this study, shear force-lateral displacement diagrams were obtained for short column specimens. By using the graphs, defining shear hinges for short column region is possible for future studies. Also by using the graphs ductility of the shear hinge can be taken into account. The effect of the proposed retrofitting methods on the shear hinge behavior of the assembly could only be obtained by performing a hysteretic analysis. Also the hysteretic diagram can allow to predict moment hinge behavior later.

The short column without any retrofitting carried a maximum load of 275,193KN. The SIFCON coating increased the shear force carrying capacity of short column by 2.18 times, reaching the value of 601,522KN. Placing rubbers around the short column region increased the total load carried by 4 times when compared with the non retrofitted column. The short column with SIFCON coating and rubber damper replacement provided a maximum shear force of 1091,822KN. The results can be seen in Figure 12.

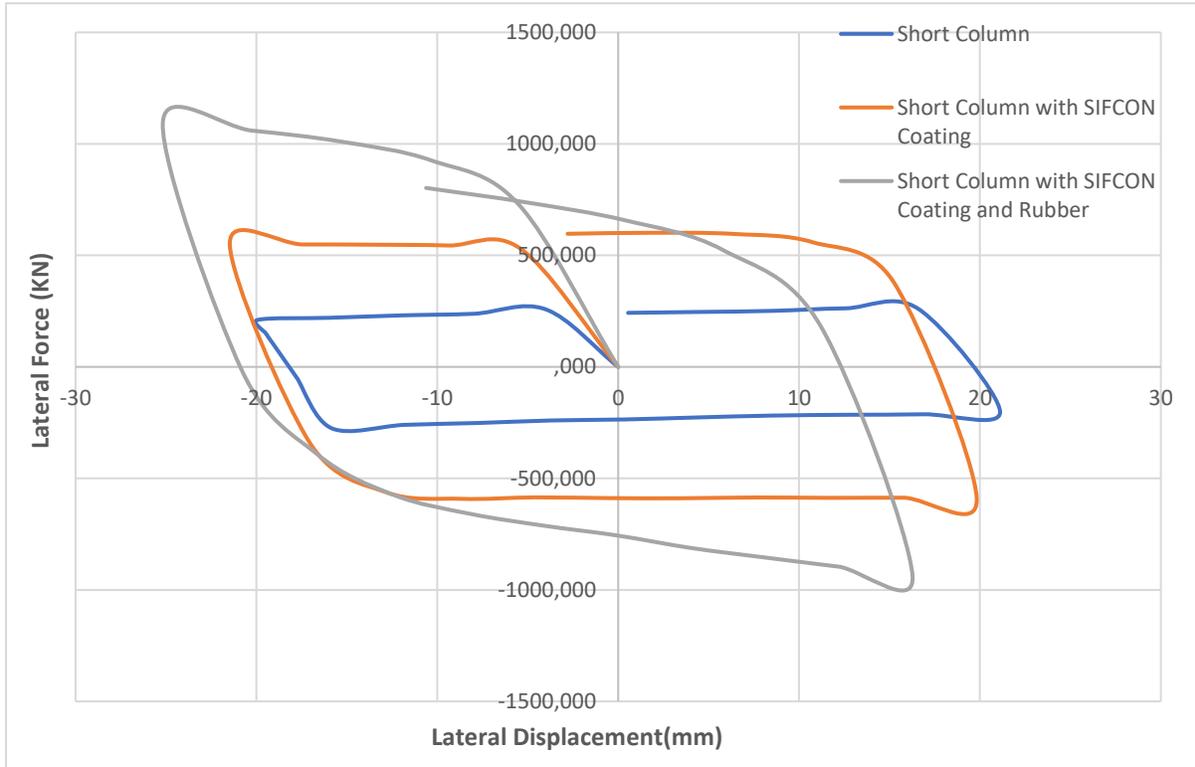


Figure 12. Shear Force-Lateral Displacement Diagrams of Short Column Assemblies for one Cycle

The proposed retrofitting methods provided ductility to the short column assembly. The areas under the curves can be calculated approximately by using trapezoidal rule. The approximately calculated areas can be used for comparison. The short column without any retrofit consumed and energy of 19416,107KNmm. The short column retrofitted by SIFCON consumed an energy of 40469,245KNmm in one cycle. This means an increase by 2,08 times of non retrofitted specimen. The short column with SIFCON coating and rubber damper replacement consumed 54889,288KNmm energy. This is 2,82 times of the non retrofitted specimen. The results can be adopted to model shear hinge and moment hinge.

3.2 Stress condition

In Abaqus, after analysis, Misses stresses can be observed for elements. Misses stress is the stress determined according to the Von Misses criterion to understand if yielding of material has started or not. If we observe the rebars, it's seen that in all models, in the confinement rebars inside the short column, Misses stresses reached around 523-550MPa (Figure 14) stress which indicates that the confinement rebars yielded. Combined effect of vertical loads and big amount of shear loads due to the short column behavior, made the rebars yield. However, due to the strain hardening of steel, as seen in Figure 4, the maximum strength of steel was 553MPa, so steel rebars remained in the zone before collapse. As seen in Figure 14, Misses stresses reached 550Mpa in the model without any retrofitting, 523MPa in the model with SIFCON coating, 542 MPa in the model with SIFCON coating and rubber dampers. The stress distribution was similar in every model, because the lateral displacement loading and vertical loading was same.

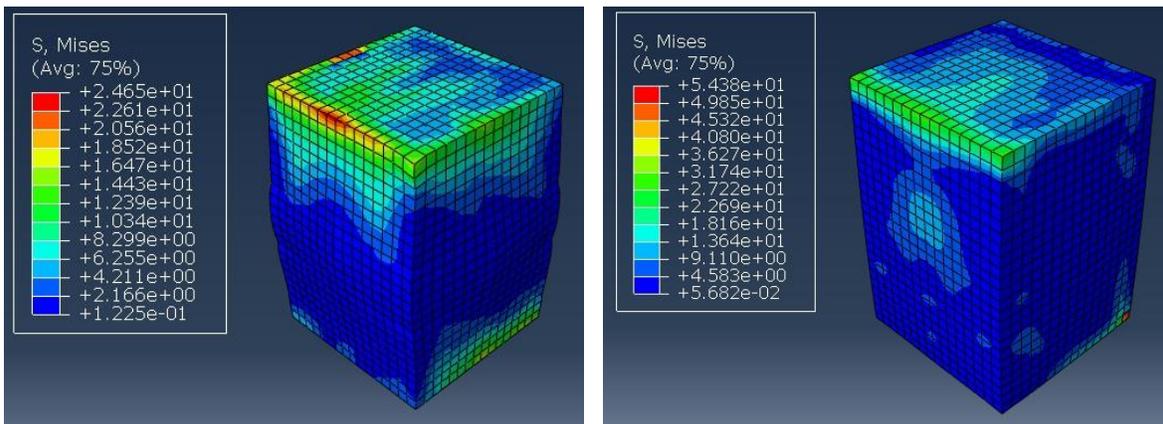


Figure 13. (a) Misses Stresses in Non Retrofitted Short Column; (b) Misses Stresses in Short Column with SIFCON Coating

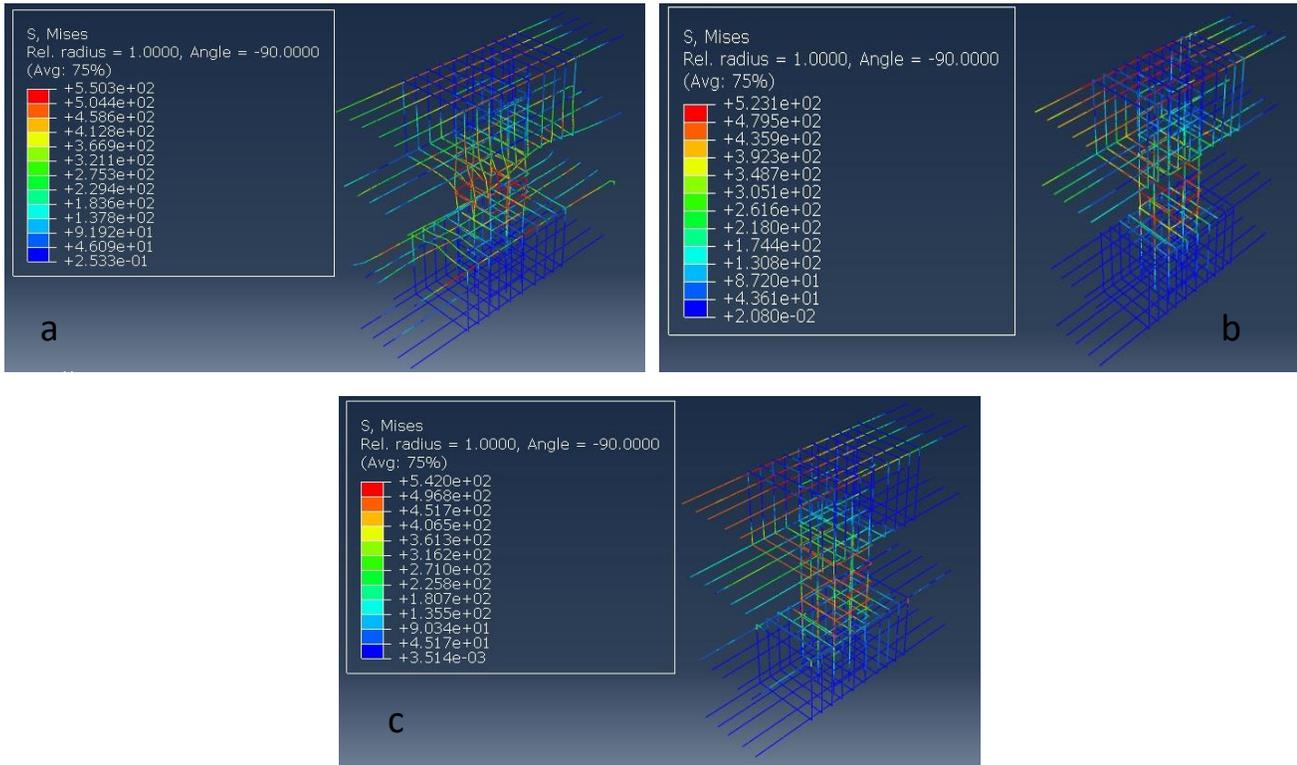


Figure 14. (a) Misses Stresses in Rebars of Short Column; (b) Misses Stresses in Rebars of Short Column with SIFCON Coating; (c) Misses Stresses in Rebars of Short Column with SIFCON Coating and Rubber Dampers

In the short columns, Misses stress distribution can be seen Figure 13. In light blue regions Misses stresses reached around 8-13MPa which indicates that they exceeded the tensile strength of concrete. Cracks can be expected in most of regions of non retrofitted short column specimen, because the stresses exceeded the tensile strength of concrete (2,20 Mpa). However, in the specimens with SIFCON coating, damaged region was decreased. The region where equivalent Misses stress is bigger than the tensile strength was smaller. High stresses around 246-317MPa levels were only seen at the top and bottom regions of columns where loading from the top beam is transferred to columns.

If the Misses stresses is observed in Figure 15, it can be seen that, applying rubber dampers around the region changed the behavior. In the specimen with rubber dampers around the short column, the SIFCON layer experienced less stresses than the other specimen. However in both of the cases, especially in the inner region of SIFCON, where the coating is experiencing stresses transferred by short column, Misses stresses (40,97MPa-23,85MPa) exceeds the tensile strength of the material. This indicates that despite the high steel fiber ratio of SIFCON, still conventional coating with rebars can be needed in seismic retrofit applications. Damage and failure with diagonal cracks is expected in SIFCON coating especially in regions where tensile strength of material exceeded. However, SIFCON coating increased the short column region’s shear strength.

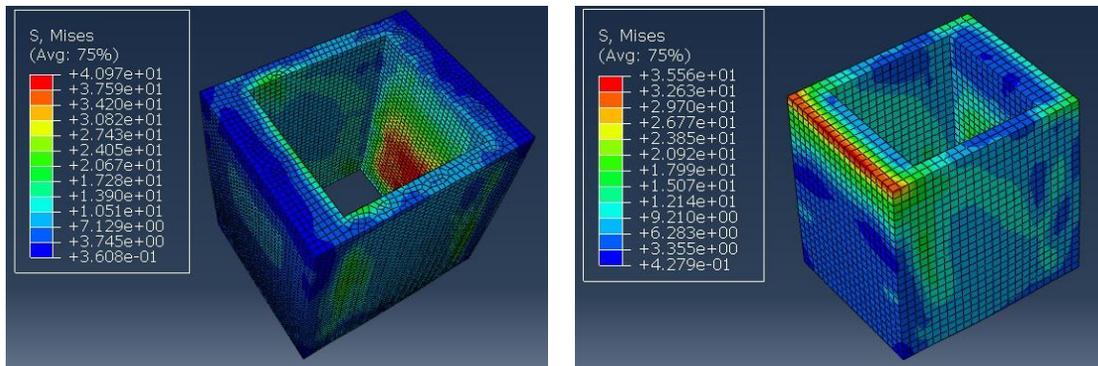


Figure 15. (a) Misses Stresses in SIFCON in Specimen with Coating Only; (b) Misses Stresses in SIFCON in Specimen with Rubber

4. Conclusion

Short column behavior is a serious problem in many buildings. Most of the time designers do not assume them to be a “short column”. Due to the mistakes in construction site, during earthquakes, these elements are subjected to big shear forces which they are not designed to resist against. In our country, insufficient confinement is a common problem in columns as seen in previous earthquakes, short column behavior makes the situation even more risky. In a previous study (Meral, 2019) it's concluded that in a building 40 to 60 percent of columns can collapse if the buildings contain short columns. In the previous study, for modelling short columns shear hinges were used in addition to axial load hinges and moment hinges. Defining shear hinges is important for exact modelling, and shear hinge ductility is not defined. To overcome those problems, in this study two retrofiting methods were proposed. One of them was SIFCON coating and the other one is increasing the shear force and energy dissipation of the short column region with additional rubber dampers. The material properties were taken from the experimental data existing in literature and Abaqus is used for analysis. As a result, it's seen that; the SIFCON coating increased the shear force carrying capacity of short column by 2,18 times when compared with non-retrofitted specimen, whereas additional rubber dampings around the short column region increased the total load carried by 4 times. Also the energy dissipation of the region increased by 2,02 to 2,82 times when compared with non-retrofitted situation. These results are promising for increasing the ductility of the short column regions. In this study, a disadvantageous behavior caused by short columns, tried to be converted to an advantageous behavior by increasing the energy consumption by using practical and fast retrofiting methods. By using different kind of coating or damping materials or systems the behavior can be improved more in following studies.

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