

MODELLING AND THE BEHAVIOUR OF ICF WALL STRUCTURES

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ABSTRACT:

In that study, first, the behaviour of insulated concrete form walls with and without openings were analysed numerically by Abaqus and Sap2000 under different axial pressure levels. In screen grid insulated concrete form wall specimens, the lateral load capacity varied between 152kN to 362.6kN. The lateral load capacity of flat insulated concrete form walls varied between 160.17kN (in zero axial pressure) to 593.42kN (under an axial pressure which is equal to 35% of characteristic concrete strength). Later, a three-story structure was considered, to be constructed using screen-grid insulated concrete forms, flat insulated concrete forms, and conventional walls. According to the pushover analysis, it was seen that the structures showed nearly a linear elastic behaviour and the structures are rigid. By using screen grid insulated concrete form walls, it's possible to have a lateral load capacity which is 56% of the capacity of structure with conventional walls. By using flat insulated concrete form walls the capacity increased to 69% of the capacity of structure with conventional walls. The ICF system can be considered as an alternative fast construction method if rigid structures are aimed to be designed.

1. INTRODUCTION

In the past years many major earthquakes caused catastrophes around the world. The observations in the previous destructive earthquakes revealed that RC structures were constructed as non-ductile moment frame structures. It's widely known that energy consumption is limited in such structures thus, the collapse of columns due to shear forces lead the structures fail during strong ground motions. Insufficient detailing of confinement rebar in plastic hinge zones was a common mistake and this type of mistake was detected in many collapsed buildings after big earthquakes including 1994 Northridge, 1999 Kocaeli-Düzce, 2010 Maule and 2023 Kahramanmaraş. Despite the major changes in controlling mechanism and improvement of overall construction quality in the past decades in developing countries, the society and sector still have not eliminated the errors in construction process entirely. However, actions must be taken to build earthquake-proof structures rapidly because major earthquakes (magnitude 7 or higher) are expected in big cities like Istanbul. In a previous study, the possibility for a major earthquake in Istanbul was given as 62% (± 15) until the year 2030 (Parsons et al. 2000).

To survive in earthquakes, another strategy is increasing the number of RC structures that rely on shear walls to resist lateral forces. In 1985 in Vina Del Mar, Chile, magnitude 7.9 earthquake happened however a big catastrophe was not observed in the region. As understood from the observations after the quake, the obligation of constructing shear walls due to the seismic regulations prevented an expected catastrophe despite the low workmanship quality and engineering quality of Chile in that period of time (Ersoy 2011). In Türkiye, the observed good behaviour of shear wall dominated structures which were built by tunnel formwork system in big earthquakes supports the effectiveness of that strategy. There happened attempts to build shear wall dominated tunnel formwork structures faster. Insulated concrete formwork (ICF)

system was developed to reduce the workmanship by not re-using the form of concrete. Also, the form itself is an insulation material. There are different types of such kind of forms and one type of them can be seen in Figure 1 (Tovey et al. 2007).



Figure 1. Some Examples of ICF Blocks (Tovey et al. 2007)

Steel reinforcement rebar can be placed inside the formwork as seen in Figure 2 (Arfa construction website). The rebar can be placed in both edges of formwork or just to the middle of the wall cross section as seen in Figure 3 (Arfa Construction Site). Fictitious narrow columns can be formed inside the holes of formwork also. The form system gives freedom to designers to use different arrangements of rebar inside the forms. The form is made up of insulation materials like EPS, so inside the form some parts can be cutted and bigger holes can be provided easily for fictitious narrow columns. This method allows designer to provide confinement pressure to concrete and therefore confined concrete behaviour can be used in modelling.



Figure 2. Construction Process of ICF Wall System (ARFA Construction Website)

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Figure 3. Placement of Vertical Rebars Inside Insulated Forms as One Layer or Two Layers (ARFA Construction Website)

Depending on the form type, the insulating forms can cause the formation of rectangular spaces on the wall. This type of wall is called screen greed insulated concrete form wall (Screen greed ICF wall). In a previous study (Lopez and Leiva 2017), the behaviour of a screen greed ICF wall was investigated experimentally. In Figure 4, the screen grid ICF wall used in experimental study is seen. In that study, vertical rebars were constructed as one layer just in the middle of cross section.



Figure 4. An Example Of Screen Grid ICF Used In Previous Study (Lopez and Leiva 2017)

Despite the development of ICF wall system, there's debate on the design and modelling of ICF wall structures. Mircea and Crutescu (2010) found that the behaviour of structures built with 200mm thick ICF wall system was in linear-elastic range under design earthquake spectrum in a region where 0.32g maximum ground acceleration is expected. They recommended using a reduction factor of 1.5 according to the dictations of Eurocode 8 in their study and they emphasized that in ICF wall structure, energy dissipation can be achieved in coupling beams only and the behaviour indicates a shear failure risk. To increase ductility they suggested creating confinement pressure in end zones of wall.

In the code of the DSA (Division of State Architect) rules are determined for ICF wall systems which are composed of a solid reinforced concrete wall between insulation panels interrupted only by plastic or metal cross-ties. It's said that the ICF wall system must comply ACI (American Concrete Institute) requirements and ICF wall systems are allowed only in one or two story structures (IR19-6 DSA code 2022). Also it's said that shear walls constructed with ICF have numerous closely spaced planes of discontinuity due to the presence of cross tie webs and test data is required to demonstrate the equivalence of this condition with conventional shear walls (IR19-6 DSA code, 2022).

Dusicka and Kay (2009) performed a quasi static loading on an ICF wall and investigated its behaviour under lateral load. The insulating forms used in that study were composed of prefabricated bricks made up of recycled materials such as wood products and recycled polystyrene. The results showed that in cyclic lateral loading, the ICF grid wall specimens showed more ductile behaviour when the wall's length is bigger compared to its width. The system's potential for resisting deformations of drifts beyond the initial cracking or yielding was seen. The

overall behaviour demonstrated that the system can be successfully implemented in areas of high seismicity (Dusicka and Kay 2009).

Solomon and Latha (2018) performed lateral quasi static cyclic loading to ICF specimens which had height of 1m and width of 0.5m. The specimens had 60mm thick core concrete, horizontal and vertical rebars had a distance of 20cm and EPS was used as an insulating form material. The specimens showed nearly a linear elastic behaviour during lateral loading. The results showed that ICF wall panels were capable of resisting lateral loads and the wall panel was recommended for the construction of seismic resistant buildings.

Asadi et al. (2016) studied the ductility coefficient for screen grid insulated concrete form walls. They compared the pushover results obtained by Abaqus with previous experiments. The numerical results had some acceptable discrepancy and showed good agreement with experimental results. In the study, reduction factor due to ductility is determined as 3.15 and the screen grid wall system's ductility was found as acceptable for high seismic risk zones.

Lopez and Leiva (2017) performed in plane lateral cyclic and monotonic loading to screen grid ICF wall specimens and understood the behaviour. One of the specimens can be seen in Figure 4. Their specimens showed flexural failure rather than shear failure and thus they decided to model the walls by using plastic hinges at the base of wall and they performed nonlinear static and nonlinear dynamic analysis to an example structure which was modelled by ICF walls and conventional shear walls. Nonlinear models and parameters that characterize the hysteretic behaviour of ICF walls were based on the obtained and calibrated experimental results. Response modification factor due to ductility was assumed as 4 in that study for linear preliminary design. The results showed that the example structure's performance point remained in linear elastic range in nonlinear static and nonlinear dynamic analysis.

The Insulated Concrete Form (ICF) wall system is a viable alternative for rapid construction; however, further investigations are required to clarify its structural behavior and modeling requirements. While certain regulatory standards, such as those by the DSA (IR19-6 DSA code 2022), limit these systems to two-story buildings based on the assumption of brittle shear failure, experimental data from Lopez and Leiva (2017) indicates a ductile flexural failure mode. In their research, plastic hinges were observed at the base of the walls, which led to the proposal of four-story ICF models for seismic regions. For practical engineering applications, predicting whether a screen-grid ICF wall will exhibit shear dominated failure or flexural failure is essential. The entire structure may require complex nonlinear modeling. Since common design softwares like SAP2000 do not feature a dedicated element for screen-grid ICF walls, a practical yet reliable modeling approximation is necessary. In this study, screen-grid ICF specimens were first analyzed in Abaqus using 3D solid elements to capture the detailed nonlinear response. Abaqus was selected due to its capacity to provide a close approximation of experimental results through 3D solid modeling, as supported by recent studies (Koman 2024, Chabi et al. 2025). This approach follows the modeling success seen in other complex systems, such as masonry (Koksai et al. 2016). This detailed analysis provided a basis for developing a more accessible modeling strategy in SAP2000 using standard shell elements. The objective is to establish a validated calibration method that enables engineers to simulate behavior of ICF walls

without the need for complex 3D simulations. Finally, nonlinear incremental static analyses were performed on a prototype structure to compare the seismic capacity of different ICF arrangements against conventional wall systems.

2. ABAQUS MODELLING OF WALLS

2.1 Modelling of Materials

The Concrete Damaged Plasticity (CDP) model in Abaqus was employed to simulate the behaviour of concrete. The CDP model predicts the residual deformations of materials that were subjected to stresses. Within the framework of Von Mises and similar failure theories, stress is partitioned into two tensors: hydrostatic and deviatoric. The theory assumes that although volume changes due to hydrostatic pressure remain within the elastic range, such stresses do not cause residual or plastic deformations. Only shear stresses can cause plastic permanent deformation in the material. The theory uses the second invariant of the stress tensor (J_2) and suggests that permanent deformations is expected if this invariant exceeds a certain limit. The expression for J_2 can be found in equation 1 (Koman 2024). In this context, σ represents normal stresses, and τ represents shear stresses.

$$\frac{1}{6}[(\sigma_{xx} - \sigma_{yy})^2 + (\sigma_{yy} - \sigma_{zz})^2 + (\sigma_{xx} - \sigma_{zz})^2 + \tau_{xy}^2 + \tau_{xz}^2 + \tau_{yz}^2] = r^2 \quad (1)$$

The Drucker-Prager criterion considers both the deforming deviatoric stress tensor and the volume-altering hydrostatic pressure, which the Von Mises criterion does not account for. This can be described as follows (Kuruşçu, 2012).

$$F(I_1, J_2) = \alpha I_1 + \sqrt{J_2} - K \quad (2)$$

In equation 2, I_1 represents the first invariant of the stress tensor, while J_2 is the second invariant of the deviatoric stress tensor. The parameters α and K are coefficients related to cohesion and the internal friction angle. The Concrete Damaged Plasticity (CDP) model is an adaptation of the Drucker-Prager criterion, incorporating a previously proposed yield surface and subsequent modifications from the literature, which account for the differential evolution of tensile and compressive strengths. Under these modifications, the yield surface in the deviatoric plane is no longer restricted to a circular shape, as its geometry can be precisely defined through the K parameter. (Al Shaikh and Falah 2014). The stress-strain relationship for concrete was modelled as shown in Figure 5 in Abaqus (Obadiat 2011) with the degradation parameter for compression elasticity d_c set to zero. The strain corresponding to maximum stress was assumed to be 0.0022 (ϵ_0) for C30 concrete, with the modulus of elasticity taken as 31000 MPa. However, cubic test results must be implemented in Abaqus software. To determine stress values and corresponding inelastic strain values in Abaqus, the method explained in a previous study was used (Incullet 2016).

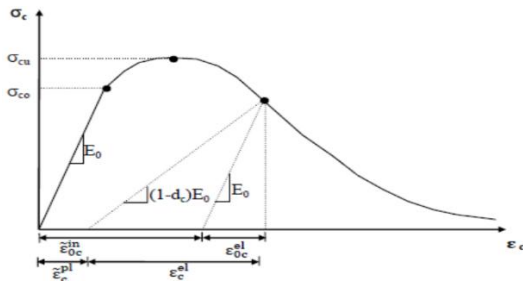


Figure 5. Stress Strain Relationship of Concrete (Obadiat 2011)

The stress-strain behavior under tension was assumed to be linear up to the material's tensile strength. Concrete's tensile strength can be assumed by using its characteristic compressive strength as follows:

$$f_{ctk} = 0.7 \times (f_{ck}^{0.5}) \quad (3)$$

Beyond the point of maximum tensile strength, the stress-strain curve was modelled with an exponential decrease. Plastic deformation values were used, and the d_t parameter (which represents the factors that reduce the elasticity of concrete under tension) was set to zero. Additional parameters were required for the CDP model in Abaqus. The dilation angle (expansion angle in the p-q plane), eccentricity (the ratio between the tensile and compressive strengths of concrete) and the f_{bo}/f_{co} ratio (the ratio between compressive strengths under bidirectional and unidirectional loading) were assumed to be 38 degrees, 0.1, and 1.16, respectively for C30 concrete. These parameter assumptions were based on a previous study, where the numerical simulation closely matched the experimental results (Obadiat 2011).

2.2 Properties of Wall Specimen And Loading Conditions

To validate the Abaqus results the specimen used in a previous experimental study was chosen (Lopez and Leiva 2017). The specimen can be seen in Figure 4. The behaviour of specimen was compared with a wall specimen without any openings under different axial pressure levels. In the previous study the specimens were categorized into two groups, each constructed using a different form type. Screen Grid ICF specimen had a rectangular cross-section with dimensions of 1200 mm in length, 200 mm in thickness, and 2135 mm in height. The walls were constructed using forms that have dimensions of 1200x310x200 mm, with openings of 132x100 mm, spaced 200 mm (from center to center) horizontally and 305 mm (from center to center) vertically. The specimens were tested as simple vertical cantilevers, securely anchored to the laboratory's strong floor via RC foundation block. A rectangular 250x250 mm RC beam was constructed at the top of each wall to transfer lateral loads to the specimens during the experiments (Lopez and Leiva 2017). In Abaqus analysis the 250x250 mm RC beam was modelled also. The reinforcing steel used for the walls was specified as A630-420H deformed bars with a yield strength of 420 MPa according to Chilean standards as indicated in another study where same specimens were used (Lopez et al. 2021). The equivalent local materials were considered to be used for the analysis. For concrete C30 concrete was considered and B420C steel was used in the modelling. That way experiments could be planned in the future. The steel material's mechanical properties can be seen in a prior study (Koman 2025) where strength of material had been obtained with the tests of local producer company. For the determination of stress-strain graphs, the method explained in Turkish Building Earthquake Code 2018 (for nonlinear analysis) was applied the previous study (Koman 2025). Same approach was adopted here. The steel for longitudinal rebars had a strength of 491 MPa yield strength, 553MPa tensile strength.

However, according to the measurements of tensile tests of steel material, the strength varied between 335MPa to 376MPa for $\phi 8$ and $\phi 16$ bars. Also, according to the tests of concrete material the compressive strength was detected as 27.7MPa (Lopez et al. 2021). Due to the unexpected material strength differences between planned and measured values of materials in previous experimental studies (Lopez and Leiva 2017, Lopez et al. 2021) first, a validation was performed using the mechanical properties of materials during experiments. In the Abaqus analysis for

validation, the steel's yield strength was reduced to 335MPa and its tensile strength was reduced to 377MPa. The concrete's cubical strength was reduced to 31.5MPa. Later a parametric study was performed using local materials. In Abaqus analysis in that study, $\phi 16$ (with a diameter of 16mm) bars were used as vertical rebar whereas $\phi 8$ bars were used as transverse reinforcement. The reinforcement was assumed to be replaced as one layer in the middle like the one in Figure 3. A linear beam element with 2 nodes (B31) was used in Abaqus for the modelling of rebar. In Figure 6, results of previous experimental study (Lopez and Leiva 2017) can be seen. The properties of ICF wall specimen and rebar can be seen in Figure 7. Specimen R4 from past study was validated in this study at first.

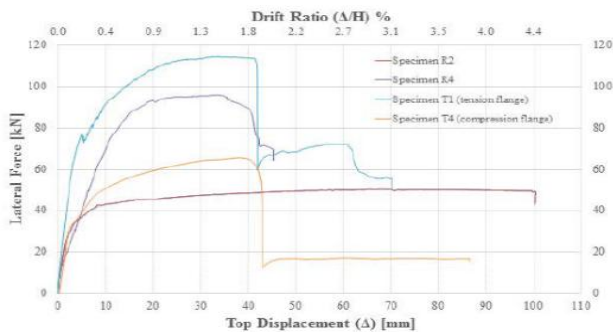


Figure 6. Experimental Load Disp. Curves of Screen Grid ICF wall specimen (R4) (Lopez and Leiva 2017)

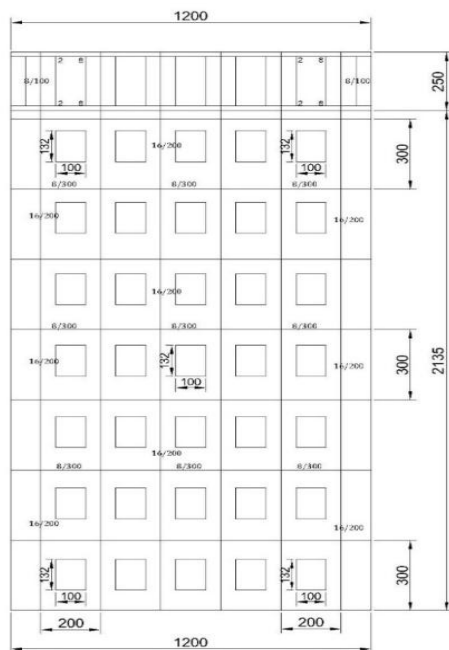


Figure 7. Dimensions (mm) and Rebars of Screen Grid ICF Wall Model

50mmx50mm solid elements named C3D8R were used in the analysis. This is a cubic element with 8 nodes and reduced integration. In Figure 8 the mesh of the screen grid wall specimen can be seen.

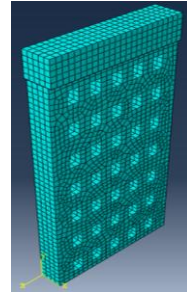


Figure 8. Mesh of The Screen Grid ICF Wall Model

In Abaqus, lateral displacement was applied to the top beam with 250x250 mm cross sections. The lateral displacement increased to 30mm in 6 seconds in a dynamic analysis. In Abaqus either explicit or implicit dynamic analysis can be used. Implicit dynamic analysis uses Newton-Raphson iteration method to solve equation of motion and it requires more computational power. However explicit dynamic analysis uses central difference method for solving equation of motion numerically. Central difference method solves the equation of motion by not constructing the mass, stiffness, damping matrices in every step. Instead, the following step's displacements were found by using the displacements of previous two steps. Also, to assume that the explicit dynamic analysis represents a quasi-static loading done in real experiment inertial forces must be kept under a level. By controlling the kinetic energy /total internal energy ratio, this can be achieved. This ratio must be smaller than 10%. The more detailed information about analysis type can be found in a previous study where historical masonry wall analysis was performed by Abaqus (Demir 2012).

There were two types of walls in the analysis. Screen grid ICF wall behaviour was compared with wall which does not contain any openings. The second type of wall without any openings will be named as "Flat ICF wall" here in the following sections. Different axial pressure levels on the top surface of transfer beam were assumed including: zero, $0.15f_{ck}$, $0.25f_{ck}$ and $0.35f_{ck}$ axial pressures. In Turkish Building Earthquake Code 2018, $0.35f_{ck}$ is a limit value for design of highly ductile RC shear walls. For screen grid ICF wall due to the openings the vertical parts resisting the axial pressure, already exceeds that limit.

2.3 Results of Abaqus Analysis

Lateral load displacement curves were obtained after the analysis. First, the behaviour of screen grid ICF wall specimen which carries zero axial pressure was compared with the experimental results of previous study (Lopez and Leiva 2017). In the previous study, screen grid ICF wall specimen carried 95.5KN maximum lateral load in monotonic lateral loading. The drift corresponding to the maximum load was 33.2mm. At the end of test the load decreased to 64.2KN and the displacement at failure was 38.4mm (Lopez and Leiva 2017). In Abaqus in the analysis of specimen for validation, a maximum load of 127.7 kN at 28.7mm lateral displacement was obtained as seen in Figure 9. The discrepancy between experimental and numerical analysis can be explained by the nature of numerical simulations. In the previous study where a numerical simulation was performed by Abaqus to simulate the behaviour of screen grid ICF wall around 6.5% discrepancy was detected between experimental capacity and numerical capacity (Asadi et al. 2017). In another previous study where RC frames containing infill walls were modelled and simulated in quasi-static lateral loading, around 15-20% discrepancy was detected between the numerical results and experimental results (Al Shaikh and Falah 2014). Because in

Abaqus, factors like element size and type affects the results. Smaller sizes rather than 50mm x50mm must be used, however this requires a computational cost. In Abaqus rebars are assumed to have perfect adherence inside concrete. This assumption neglects the micro-slippage (bond-slip) that occurs in reality in experiments, thereby a slightly bigger stiffness is expected. In a past study (Li et al. 2019) a graph was presented to show the variation of the dilation angle with the compressive strength. Dilation angle of concrete must be decreased with concrete's compressive strength. In that study also, trials were done and the dilation angle was decreased to 32 degrees to model the concrete of past study (Lopez and Leiva 2017), however a meaningful decrement in capacity of wall could not be seen. Therefore, here, the discrepancy was thought as acceptable.

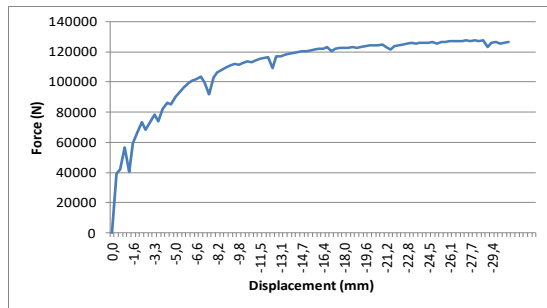


Figure 9. Load Disp. Curve of Screen Grid ICF wall specimen (R4) in Abaqus

Later analysis was continued in Abaqus analysis with local materials as explained before. Maximum load was found as 152KN at 26.46mm lateral displacement for the specimen which carries zero axial load. Later, the analysis was renewed by applying $0.15f_{ck}$, $0.25f_{ck}$ and $0.35f_{ck}$ axial pressures to the top. When $0.15f_{ck}$ axial pressure was applied, the maximum lateral load carried was 193.76KN and the corresponding displacement related with maximum load was 10.4mm. When $0.25f_{ck}$ axial pressure was applied, the maximum load was 366.57KN and the corresponding displacement with maximum load was 8mm. In $0.35f_{ck}$ axial pressure case, the system was overloaded in axial direction causing a lower lateral load capacity of 136KN. The results can be seen in Figure 10.

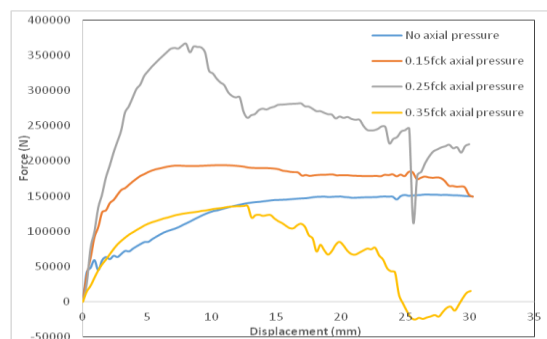


Figure 10. Load Displacement Curves of Screen Grid ICF Walls in Abaqus

By using the same method, the behaviour of Flat ICF wall without any openings was analysed. When there's no axial pressure, the behaviour was similar with screen grid ICF wall. The maximum lateral load was determined as 160.17KN at 22.9 mm lateral displacement. When $0.15f_{ck}$ axial pressure was applied, the maximum lateral load carried was 403.99KN and the

corresponding displacement related with maximum load was 8mm. When $0.25f_{ck}$ axial pressure was applied, the maximum load was 574.9KN and the corresponding displacement with maximum load was 10mm. In $0.35f_{ck}$ axial pressure case, the maximum load was determined as 593.4KN in 5.91mm displacement. The results can be seen in Figure 11. Also, In Table 12, results were summarized.

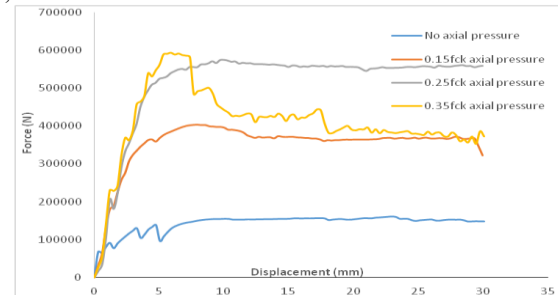


Figure 11. Load Disp. Curves of Flat ICF Walls in Abaqus

	Axial Press. on Wall	Max. Load Exp. (kN)	Max. Load Abaqus (kN)	Disp. (Max. Load) (mm)	Disp. Max. Load Abaqus (mm)
S.G. ICF (Lopez and Leiva 2017/R4)	0	95.5	127.7	33.2	28.7
S.G. ICF With C30	0	-	152	-	26.46
S.G. ICF With C30	$0.15f_{ck}$	-	193.76	-	10.4
S.G. ICF With C30	$0.25f_{ck}$	-	366.57	-	8
S.G. ICF With C30	$0.35f_{ck}$	-	136	-	12.76
Flat ICF With C30	0	-	160.17	-	22.9
Flat ICF With C30	$0.15f_{ck}$	-	403.99	--	8
Flat ICF With C30	$0.25f_{ck}$	-	574.9	--	10
Flat ICF With C30	$0.35f_{ck}$	-	593.4	--	5.91

Table 12. Comparison of Previous Experiments (Lopez and Leiva 2017) and Abaqus Analysis

3. SAP2000 MODELLING OF WALLS

In Sap2000, RC wall was modelled using shell elements. According to the manual of Sap2000, a shell is a three or four-node area object used to model membrane and plate-bending behaviour. Shells can be modelled as a homogeneous layer. Alternatively, the shells can be composed of multiple layers across their thickness. For layered configurations, it is possible to define orthotropic, nonlinear and temperature sensitive material characteristics. Furthermore, such layered elements are capable of capturing the localized nature of nonlinear responses. In the shells edge constraints can be assigned and shells may be loaded in any direction, along any side (Computers and Structures, Inc., 2023). To simulate quasi-static loading performed in experiments, pushover analysis was done in Sap2000. In pushover analysis lateral load is increased step by step and a nonlinear static analysis is performed. But as advised in Turkish Building Earthquake Code 2018, a nonlinear vertical loading was applied to the wall to take into the

effect of axial loadings. The lateral pushover analysis started by using the conditions at the end of vertical nonlinear static loading in Sap2000. P-delta effects were considered in Sap2000 during the analysis. In Sap2000 the concrete's stress-strain relationship was modelled using Mander model. The strain at maximum stress was taken as 0.0023 and the strain at ultimate capacity as 0.0034. Just like the Abaqus model, strain hardening of steel was considered. The strain at onset of strain hardening was taken as 0.01 and the ultimate strain capacity was taken as 0.09. In the analysis the wall was divided by 30x30 grid which means 900 shell elements were used. According to the results, the flat ICF wall carried 223.40KN maximum lateral loading at a displacement of 6.43mm. The result was consistent with Abaqus analysis where the load was 160.17KN. In the case of $0.25f_{ck}$ axial pressure applied on the top of wall cross section, the axial load carried was determined as 672.1KN at 2.29mm displacement. The result was also consistent with Abaqus analysis where the specimen carried 574.9KN load. When $0.35f_{ck}$ axial pressure was applied, the maximum lateral load carried was determined as 706.74KN. The results can be seen in Figure 13.

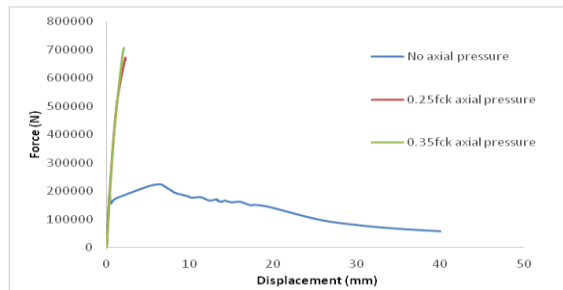


Figure 13. Load Displacement Curves of Flat ICF Walls in Sap2000

The same method was used to model screen grid ICF walls. The SAP2000 software's existing element library does not provide an element that directly represents the screen-grid type reinforcement/wall connection details. Therefore, a parametric calibration was applied to approximate the effective stiffness and yield strength of the wall elements in the SAP2000 model to the experimental and Abaqus models. Parameter reductions were selected to minimize the main characteristics of the load-displacement curve obtained from Abaqus (initial slope/stiffness, maximum load, ultimate ductility). For that purpose, a few trials were done. In the end, it was seen that assuming the strength of materials and the modulus of elasticity to be half of real values provided good agreement when layered shell elements in Sap2000 element library was used. Because in Sap2000, a wall without any openings was modelled and its behaviour must be calibrated according to the Abaqus analysis. After some trials, this calibration was found to be representative. According to the results, the screen grid ICF wall carried 152KN maximum lateral loading at a displacement of 5.14mm. The result was consistent with Abaqus analysis where the load was 152KN. In the case of $0.25f_{ck}$ axial pressure applied on the top of wall cross section, the axial load carried was determined as 374.5KN at 1.89mm displacement. The result was also consistent with Abaqus analysis where the specimen carried 366.57KN load. When $0.35f_{ck}$ axial pressure was applied, in Sap2000 vertical loading's results could not be used to start a lateral pushover loading. This explains the low lateral load capacity obtained in Abaqus when $0.35f_{ck}$ axial pressure was applied. The results can be seen in Figure 14.

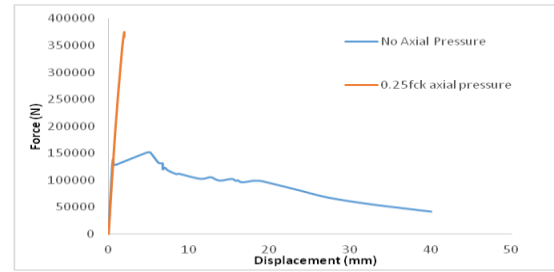


Figure 14. Load Displacement Curves of Screen Grid ICF Walls in Sap2000

4. MODELLING OF AN EXAMPLE STRUCTURE IN SAP2000

After the validation of the analysis done in Sap2000, it's decided that same modelling method by using shell elements can be used for the analysis of a 3-story example structure. The example structure was assumed to have a base area of 288m². It's a symmetric structure. In the plan it's divided to 9 sections. Each square section had 6x6 m dimensions (In Sap2000 software length is measured as 6m from the middle of one axis to the middle of other wall axis). The structure's structural system was consisted of walls and slabs only like a tunnel formwork structure. The wall thickness was taken as 250mm. The reason of that selection was based on the restrictions of Turkish Building Earthquake Code 2018 for shear walls. Dead loads excluding the self-weight of elements were assumed to be 3KN/m² and live loads were assumed to be 2KN/m² and the loads were applied as a uniform loading to the 15cm thick slabs. Four cases were assumed. In the first case, all of the walls were modelled as screen grid ICF walls. In the second case all of the walls were modelled as flat ICF walls. In the third case, the walls were assumed to be a conventional wall and vertical rebar were replaced as two layers and a confinement was assumed. In the fourth case, only the core walls of the structure were assumed to be conventional RC shear wall whereas other walls were assumed to be screen grid ICF walls. In the ICF walls the distance between vertical and transverse rebar were taken as 200mm. In the structure C30/37 concrete was used and steel with a yielding strength of 420MPa was used. The structure contains 3m length cantilever slabs on the corners. The analysis of slab's rebar was beyond of that study. The modelled structure in Sap2000 can be seen in Figure 15. Pushover analysis was performed to all structures and capacity curves were obtained. Before the lateral incremental nonlinear static loading, a nonlinear vertical loading was applied to the structures by using G+0.3Q (G indicates dead loads, Q indicates live loads) load combination as dictated by Turkish Building Earthquake Code 2018.

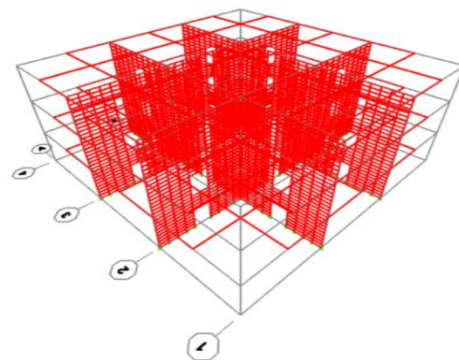


Figure 15. The Example Structure

The results of pushover analysis can be seen in Figure 16.

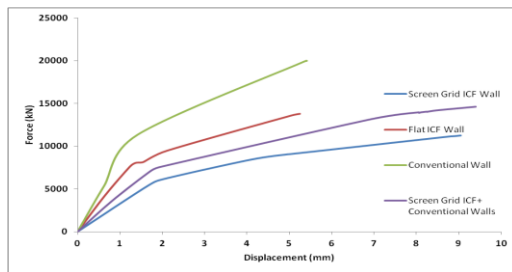


Figure 16. Capacity Curves of Structures

5. RESULTS AND DISCUSSION

In that study, first, a screen grid ICF wall specimen which was tested previously (Lopez and Leiva 2017) was analysed in a detailed 3D finite element analysis performed by Abaqus. The behaviour of specimen R4 was consistent with previous tests. Some discrepancy was expected between numerical and experimental studies due to the nature of simulation and the reasons of discrepancy were explained in section 2.3. Later, analysis was continued using equivalent local materials. Screen grid ICF wall and flat ICF wall which does not contain any openings were tested to understand the effect of openings. The comparisons were renewed under different axial load levels. In screen grid ICF wall specimens the lateral load capacity varied between 152kN to 362.6kN. Until the axial pressure level of $0.25f_{ck}$ the lateral capacity increased whereas in $0.35f_{ck}$ axial pressure level the capacity decreased. The lateral load capacity of flat ICF walls varied between 160.17kN (in zero axial pressure) to 593.42kN (under $0.35f_{ck}$ axial pressure). This indicates that when openings were removed inside an ICF wall its lateral load capacity increases by 5% (zero axial load) to 58% ($0.25f_{ck}$ axial pressure). Also, more axial force can be carried. The numerical analysis of wall specimens was renewed in Sap2000 software with shell elements. The behaviour was consistent with Abaqus results.

The flat ICF walls' lateral load capacity varied between 223.40kN (zero axial pressure level) to 706.74kN ($0.35f_{ck}$ axial pressure level). The screen grid ICF walls' load capacity varied between 152kN (zero axial force level) to 374.5kN ($0.25f_{ck}$ axial pressure level). In Sap2000 analysis, also it's seen that the removal of openings inside the wall increased the lateral load capacity. In Sap2000 analysis, similar to Abaqus analysis, it's seen that $0.35f_{ck}$ axial pressure level can be considered as an overload for screen grid ICF walls. Later, the behaviour of 3 story structures built with screen grid ICF walls, flat ICF walls and conventional RC walls were compared in Sap2000. The screen grid wall structure's capacity was obtained as 11256.01 kN. When flat ICF walls were used the capacity increased to 13803.17 kN which indicates an increase of 22%. When conventional RC wall was used the structure's lateral load capacity was increased to 19985.39kN. This is nearly 44% higher than the previous case. When Screen grid ICF walls and conventional walls were used together in structure, it was available to reach a capacity of 14595.59kN.

As seen from the analysis, the structure showed nearly a linear elastic behaviour and the structure is rigid. This result is consistent with the previous study (Lopez and Leiva, 2017) which indicates that structure's performance point remained in linear elastic range in nonlinear static and nonlinear dynamic analysis when ICF wall and conventional walls were used as a

structural system. While Lopez and Leiva (2017) modelled the ICF structure by employing plastic hinges at the base of walls (under the assumption of a predominant flexural failure) the modelling approach presented in this study bypasses the need for such preliminary assumptions or preliminary failure analysis. Instead, the fiber modelling of the walls within SAP2000 using standard shell elements is shown to be sufficient for capturing the nonlinear response of the system. In DSA code, it's said that the ICF wall system must comply ACI (American Concrete Institute) requirements and ICF wall systems are allowed only in single story or two-story structures (IR19-6 DSA code 2022).

The reason of that limitation must be questioned. Also, it's said that shear walls constructed with ICF have numerous closely spaced planes of discontinuity due to the presence of cross tie webs and test data is required to demonstrate the equivalence of this condition with conventional shear walls (IR19-6 DSA code, 2022). This study used Abaqus analysis to produce performance data across different axial load levels and provided a basis for demonstrating an equivalent modelling approach for ICF walls using standard shell elements in SAP2000. Therefore, using the fiber modelling approach here ICF wall structures can be designed and story limitation can be re-evaluated in practical engineering applications.

Furthermore, the results are consistent with the findings of Mircea and Crutescu (2010), who observed that 200 mm thick ICF wall systems remained within the linear-elastic range under the design earthquake spectrum for regions with a peak ground acceleration of $0.32g$. In accordance with Eurocode 8 provisions, they recommended a reduction coefficient of 1.5. While other researchers, such as Lopez and Leiva (2017) and Asadi (2016), used higher reduction factors in their studies, the nonlinear fiber modelling approach presented here explicitly defines structural behaviour without relying on predefined reduction coefficients. Additionally, mirroring Mircea and Crutescu's (2010) suggestion to provide confinement at the wall ends to enhance ductility, the methodology developed in this study allows for the detailed analysis of various rebar arrangements and alternative materials in future research.

6. CONCLUSION

In this study, a practical yet reliable modelling approximation for ICF Wall structures was presented. For that purpose, ICF wall specimens were modelled using Abaqus and Sap2000 and their behaviour was compared with previous experiments in literature. Later a 3-story structure using ICF and conventional walls was analysed. It was seen that the behaviour of 3 story structure is nearly linear elastic and behaviour is rigid. Therefore, the ICF wall system can be used by designers to allow fast construction and to obtain rigid structures. Different configurations of Screen grid ICF wall, Flat ICF wall, conventional wall systems can be used to achieve an appropriate design. The simulation method explained here can be used to understand behaviour. The method is based on using shell elements for nonlinear analysis in Sap2000 software and preliminary analysis for the determination of reduction coefficient or failure type of walls is not needed.

In the following studies, it's advised to use different design approaches for structures built with ICF wall system, including the usage of coupling beams or the usage of fiber reinforced high performance concretes to increase ductility. Also, new methods must be thought for the usage of the ICF wall system in 5-10 story structures to provide fast housing in areas of high seismic risk.

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