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RESEARCH ARTICLE

Nonlinear dynamic analysis of power plant air-cooled condenser (ACC) structures: An industrial application of OpenSees software

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ABSTRACT

The Air-Cooled Condenser (ACC) structure is one of the pivotal industrial buildings in Combined-Cycled Power Plants. This structure functions as a condenser of water steam, which is conveyed to it through the steam turbine generators, and accumulates the produced water and returns it to the plant's main water circulation system. While the overall behavior of ACCs under earthquake is fairly known, important details such as the seismic response modification coefficient, R, have been a matter of controversy among the involved engineers. To address these ambiguities and in order to conduct a sure design, a more precise investigation of seismic behavior and response of these structures was deemed to be in demand. Answering this want, a numerical program was created in OpenSees numerical modeling platform to generate models for ACCs of different types, dimensions, and mechanical properties. The numerical results obtained from the analysis, especially for concrete ACCs, for whom investigation of their behaviour was thought to be more necessary, accorded well with the expected seismic behaviour foreseen for these buildings.

Keywords: ACC structures; numerical modeling; software development; nonlinear dynamic analysis; OpenSees

1. Introduction

The ACC structure functions as a water-steam condenser, which is conveyed to it through the steam turbine generators, and accumulates the produced water for returning it to the plant's main water circulation system. The ACCs are fairly tall buildings containing, primarily, a main beam grid at the beam-level which is mounted on the concrete columnar posts, or steel frames, depending on the type of the ACC structure. The seismic load-resistant system in ACCs is steel bracing and concrete moment framing according to the ACC type. Whereas the braces in the steel braced frames exhaust the induced inertia forces of the earthquake through the steel material reaching the yield strength level and beyond, the columns in the concrete framed ACCs dissipate the internal inertia forces via forming plastic flexural hinges at their two-ends (see **Figure 1(b)**). The ACCs, besides in the built-material, can differ in terms of overall geometry, i.e. number and length of main spans in each principal direction, total height, and members' cross-sectional dimensions. Generally, the definition of ACC structures can be readily found in technical reports/documents produced for each particular ACC, outlining their function as well as structural design details and requirements in the Combined-Cycle Power Plants (see Ref.[1] and[2]).

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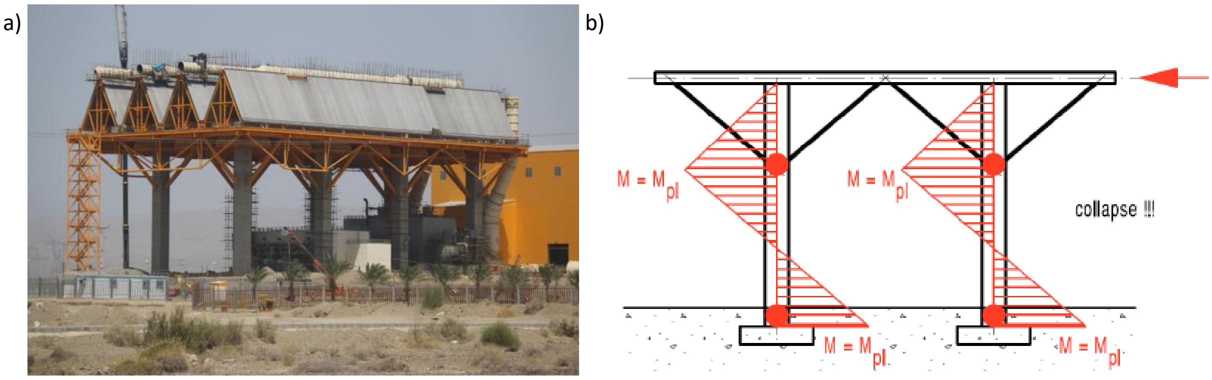


Figure 1 a. A concrete ACC structure in Kahnooj, Iran[1], b) formation of plastic flexural-hinges in two ends of concrete columns presumed in strong ground motions[2].

Concerning a robust earthquake engineering design, seismic behaviour of concrete ACCs, owing to the unconventional size of their concrete columns (reaching up to the column's cross-section's overall dimension of 270 cm (i.e., 2.70 m)), presence of the flexible roof-diaphragm, and special system of roof steel beaming and collector, demands a very thorough exploration. The investigation of ACC building seismic behaviour, in the most comprehensive numerical manner, may be performed through a nonlinear dynamic analysis utilizing robust software capable of undertaking such analysis. To this end, Open System for earthquake engineering Simulation software, i.e., OpenSees[3], was adopted. OpenSees software is an open-source computer-coded platform created by the Berkeley University with the capacity to be developed through receiving scientific and technical collaborations from different researchers/engineers worldwide. Any program made based on this platform, therefore, could be further expanded or revised towards its completion. The steel type ACCs included in the software development as part of this project were two- and three-storey steel structures as well as concrete type ACCs with and without cantilevered roof. Aiming to fulfill the research project goals, four independent programs were created, each one dealing with one of the aforementioned ACCs.

2. ACC model structural components

ACCs, according to their type, are made of different structural elements. The modeling is completed with, understandably, a certain, but not unlimited, amount of complexity and therefore not all the structural components are modeled; the members included in the models are those components which deemed to influence the seismic behaviour of the ACCs in the meaningful way. Other components are modeled either with the elastic material properties or are excluded from the final models, e.g., the connections. Some of these components are designed for the ultimate capacity of the connected members and, therefore, can be rightly assumed to remain elastic during strong ground motion events. The model elements are shown in **Figure 2** for two types of steel and concrete ACCs. The ACI 318[4] and AISC 360[5] standards were utilized for the design of concrete and steel parts, respectively. The general loading of structures was performed using the ASCE 7 code[6], and the loads specific to the ACC structure were determined from the ACC's design specification notes; this is a technical document produced and stipulated along with every power plant project, outlining the engineering design requirements specific to that project such as minimum design loads, legitimate design codes, etc. Moreover, the elastic analysis of the ACC structure and the initial design of its main members were performed using SAP software[7].

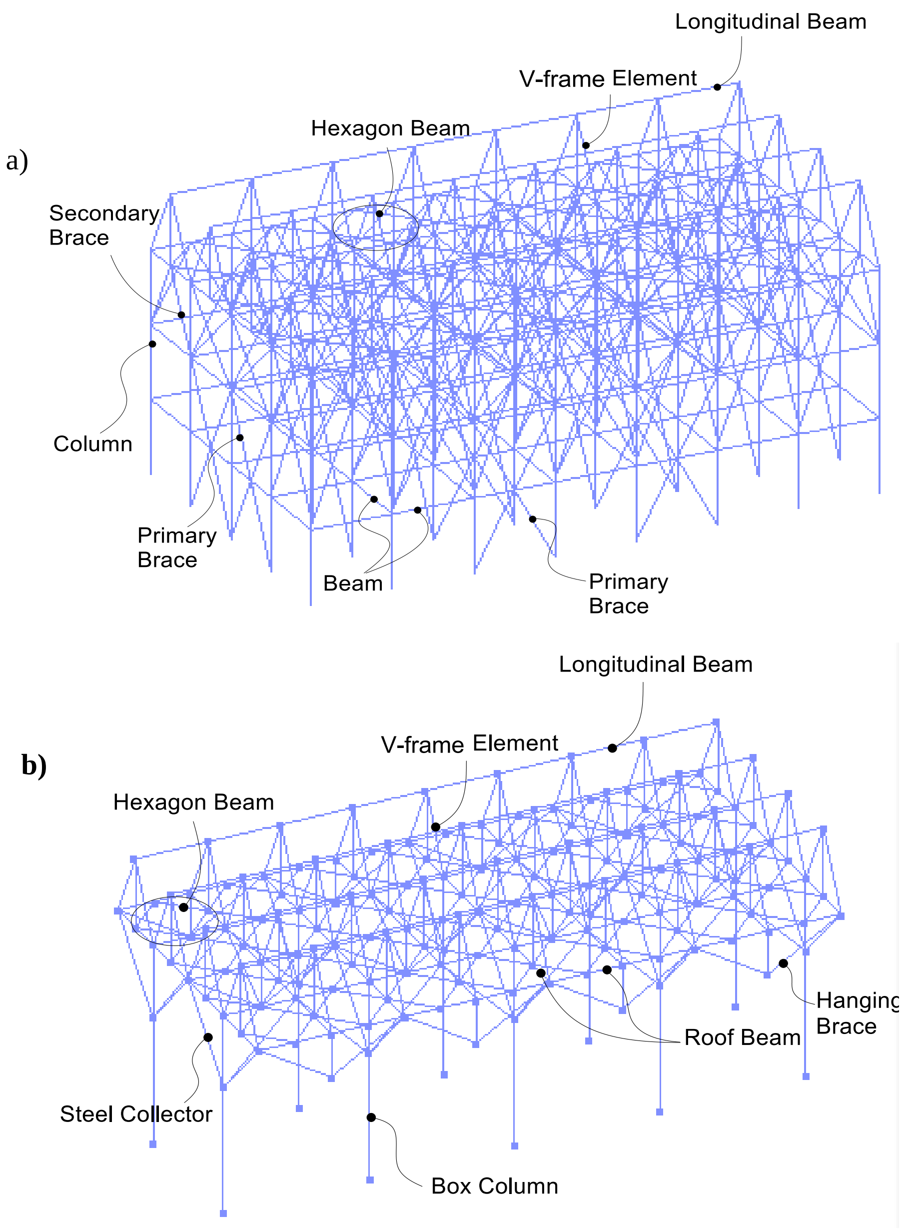


Figure 2. Various elements in the a) steel and b) concrete ACC model in OpenSees software.

2.1. Steel ACC model

As can be seen in **Figure 2(a)**, the steel ACC model is composed of multiple elements that establish the entire body of the building model. These components are box-shaped columns, beams with box- and I-shape cross-section, box braces, steel plate connectors, hexagon beams, V-frames, longitudinal beam, and pyramid-shaped lateral bracing. The Box columns are hollow box sections with a uniform thickness and equal sides. The steel material type assigned to columns is Steel02 which can account for the nonlinear properties of steel when subjected to reversed cyclic loads. The beams are either box- or I-shape with nonlinear material behaviour and Nonlinear Beam Column Element, allowing for the formation of plastic flexural hinges at the beam ends. The box-section beams are connected to columns with simple plate connectors. These plates are inserted as part of the model so that the effect of beam-to-column connection can be observed at least to some extent. The diagonal and chevron type brace elements have box cross-section comprising plate connectors at their ends or in the middle, in the case of the diagonal brace. The Steel02 material and

Nonlinear Beam Column Element are used for the braces. The hexagon beams are at the roof beam level of the ACC model with the duty of supporting cooling fans. The V-Frames are mounted over the roof beams making a support for the steam transferring pips along their longitudinal direction. The V-frame elements, according to the direction of their installation, are divided into oriented and vertical members. The pyramid-shaped lateral bracing for V-frames is supposed to provide resistance for the frames in the lateral direction and has nonlinear material properties. The longitudinal beam elements join the V-frames vertices in the model as a simplified approach for representing the V-frames connection in the longitudinal direction; the V-frame and longitudinal beam are assumed elastic. Other structural components such as steel connections, other than the brace- and beam-plate connectors, are neglected for inclusion in the final model; this modeling simplification, however, was not deemed to influence the seismic behavior of the ACC structure and its components in a meaningful way compared to the other elements already included in the model. **Figure 3** illustrates a typical steel ACC model and introduces the model elements in OpenSees software.

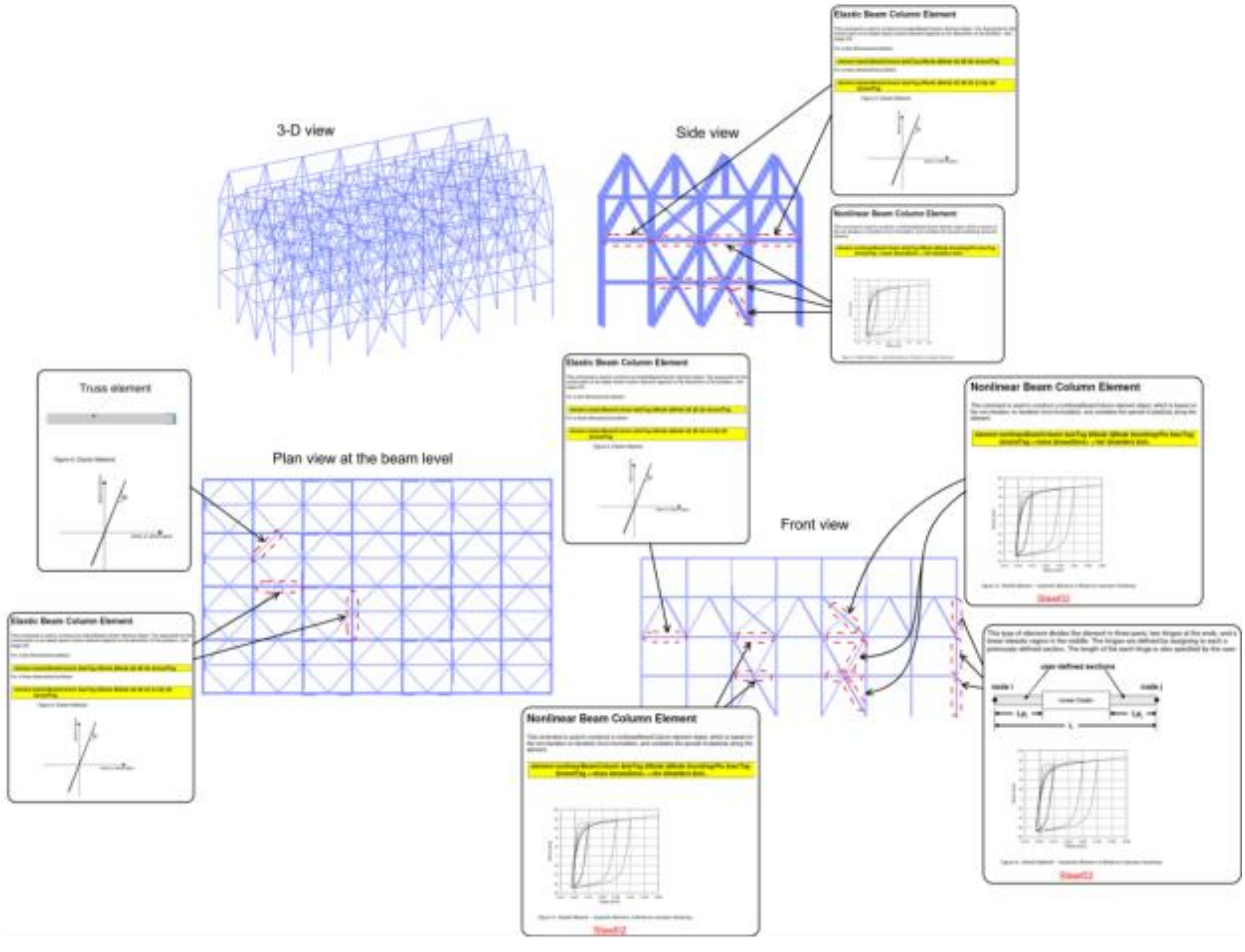


Figure 3. Structural elements and their mechanical properties in steel ACC model made in OpenSees.

2.2. Concrete ACC model

The second type of ACC is concrete made. The vertical concrete columns are hollow-box sections with a side measure of greater than 2.50 m and thickness of about 0.30 m, or thicker, with, almost, 25 m height from the foundation to the beam level. This relatively grand element is made of Concrete02 material with distinct, nonlinear behaviour in compression and tension zones, and the rebar elements are Steel02 with nonlinear material behaviour. The columns participate the most in exhausting the induced seismic forces in the concrete ACC structure and therefore shall be attended to with sufficient care during the modeling process so that a realistic representation of this building can be achieved as far as possible. The beams are at the roof level and are I-shape steel sections with the capability of undergoing nonlinear deformations. The steel collector elements, resembling branches of a tree in appearance, connect the concrete ACC's roof system to the concrete columns, similar to that of a tree trunk (see **Figure 1(a)**). The collectors are steel box sections with equal sides and are made of Steel02 material with nonlinear behaviour. The hexagon beam elements are at the beam level, providing support for the fan bridges. The V-Frames are mounted over the roof beams and support the steam-transferring pips. The pyramid-shaped lateral bracing, with nonlinear behaviour provides, lateral resistance for the elastically-modeled V-frames.

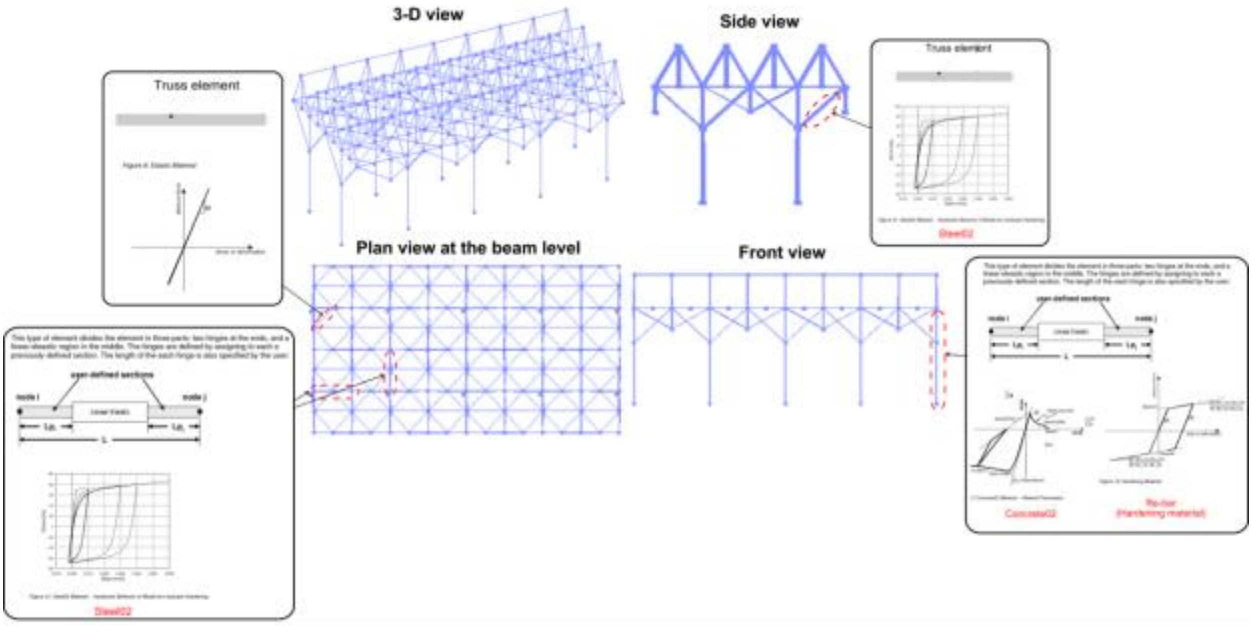


Figure 4. Structural elements and their allocated mechanical properties in OpenSees for the concrete ACC model.

3. Computer program introduction built-in the OpenSees

The program was divided into three main partitions consisting of the: program input, program body, and analyzing segment. In the program input section, the structural data such as element dimensions and materials are provided by the analyst. The program body builds the entire ACC structural model according to the given input data. Afterwards, the created models are analyzed under the gravity and earthquake loads, in due sequence.

3.1. Program input

For each ACC structure, the data specific to that structure should be defined by the analyst prior to the entire model being eventually established and analyzed. These primary data, specified by the user, are termed input data. This is the only part of the program with which the user is in direct dialogue. The input data can be introduced to the program in four sections which, in order of appearance in the code, are geometrical data, input data related to the dynamic analysis, material properties, and mechanical properties. This dividing method facilitates the program usage. The geometrical data is information that is essential for defining the overall configuration of the ACC structure (see **Table 1**). The input data concerning the dynamic analysis specifies the parameters required for conducting the nonlinear time history dynamic analysis, including the time step, earthquake duration, scale factor for the applied earthquake in the principal direction, scale factor for applied earthquake in direction perpendicular to earthquake's principal direction (i.e., secondary direction), vertical earthquake scale factor, ground-motion record in the appropriate format, viscous damping ratio, principal and secondary directions of the applied earthquake as well as the earthquake vertical direction.

Material properties are defined in order to capture behaviour of model components when undergoing various loading conditions. In the steel-built ACCs, the utilized material selected from the OpenSees material library is known as Steel02; the Steel02 material is capable of accommodating force versus displacement nonlinear hysteresis behaviour when subjected to cyclic load and, in addition, accommodates strain isotropic hardening of the steel material. For structurally less-important steel parts, steel with elastic material behaviour is selected. The relevant input parameters for the steel material are steel module of elasticity (E_s), steel Poisson's ratio (ν), and steel yield stress (F_y). In concrete-built ACCs, the behaviour of concrete is assumed as Concrete02 material; this material type has separate compressive and tensile curves and includes strain limits where the concrete tensile strength reaches zero and the concrete compressive stiffness vanishes. The corresponding input parameters for concrete are module of elasticity (E_c), concrete 28-day compressive strength (f_{pc}), concrete compressive strain at f_{pc}, concrete compressive strength of the crushing point (f_{pcu}), concrete compressive strain at f_{pcu} (epsU), concrete maximum tensile strength (f_t), and ratio of the unloading slope at epsU to the initial slope, equal to 0.4 as default value. The concrete reinforcement re-bars are hardening steel type identified with yield stress and steel modulus of elasticity. For steel parts of the ACC where the nonlinear behaviour of steel material is intended to be investigated, Steel02 material is used. The cross-section of each particular element can be defined via the section's overall dimensions and material properties.

Table 1. Cross-sectional properties of the ACC model structural components.

Concrete ACC		**Steel ACC**	
Structural element	**Cross-section**	**Structural element**	**Cross-section**
Column	Hollow-box	Column	Box
Beam	I-shape	Beam	Box and I-shape
Hanging brace	Pipe	Brace	Box
Hexagon beam	I-shape	Hexagon beam	I-shape
Collector	Hollow box	V-frame	I-shape
V-frame	I-shape	Pyramid brace	Pipe
Pyramid brace	Pipe	Longitudinal beam	I-shape
Longitudinal beam	I-shape		

3.2. Program body

The core part of the program as well as its executional apparatus resides inside the program body, containing all the coded subroutines produced to define different components of an ACC structure for assembling them together. The program body comprises partitions for defining model nodes, model elements, nodal restraints, and geometry transformation. Every component is automatically built by a certain programmed loop within the program body, allocated specifically to that duty.

3.3. Analysis

The ACC structure is analyzed for desired load conditions after the construction of the ACC model. Load conditions implanted in the program are gravity and earthquake loads. First, the gravity load is exerted on the structure as a permanent, sustained load, and then the earthquake load is applied. Concerning the gravity load analysis, the total sum of the inserted gravity load equates to the total mass of the ACC structure i.e., typically, the entire dead load plus a percentage of live and snow loads. The calculated gravity load can be obtained from the already-made design models in conventional engineering programs. As shown in **Figure 5(a)**, the gravity load is uniformly distributed among the nodes as nodal loads at the beam level. The time history dynamic analysis of ACC under a certain ground motion record in the principal, secondary, and vertical directions has also been presented in **Figure 5(b)**.

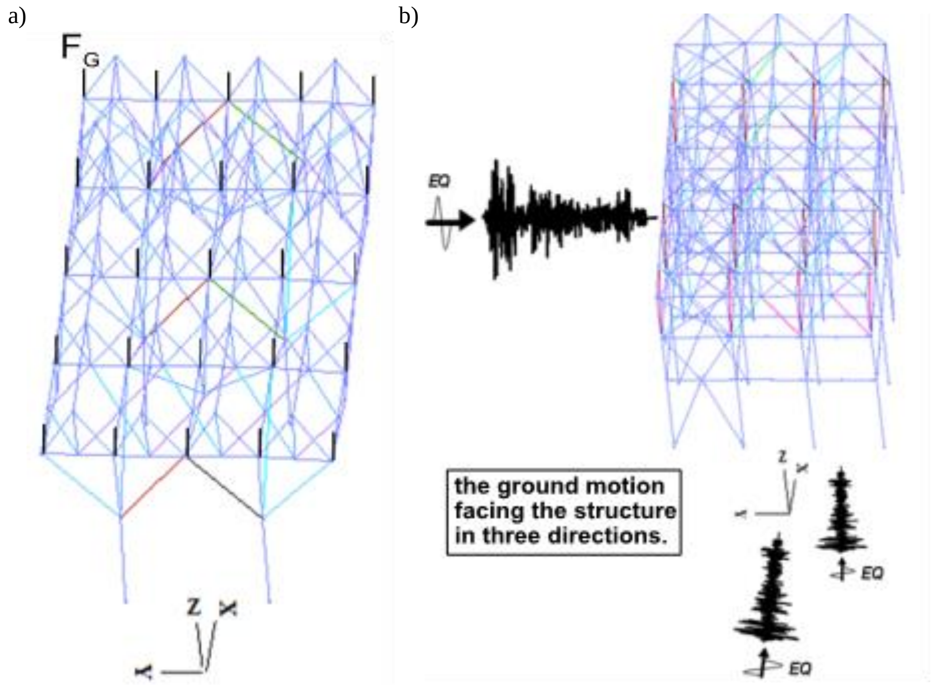


Figure 5. The ACC model subjected to a) gravity, F_G and b) earthquake loads.

4. Program output

The output files are saved in several designated folders in the text format. The files contain analysis results of model elements, including internal forces, deformations, and a brief description of the saved results. In addition, information related to natural periods and frequencies of the structure for the first twenty-five modes are recorded by the program. The ACC model displacement, while subjected to time history dynamic analysis, is displayed for a better understanding of the ACC seismic behaviour and tracing the program's possible flaws. Given the complexity of ACC models, studying the ACC seismic behaviour, after completion of the dynamic analysis, became possible through a post-processing phase.

5. Discussing the case-studies

After creating the program, two ACCs with actual industrial applications are studied consisting of a three-storey steel ACC located in Tous City, Razavi Khorasan Province of Iran, and a concrete ACC with a cantilevered-roof located in Chābahār City, Sistan and Baluchestan province in Iran. These real case studies are introduced and discussed in detail in the following chapters.

5.1. Tous' steel-built ACC

Tous project ACC is made of steel in three storeys with a roof height of +29.3 m from the concrete pedestal top level. It consists of seven spans in the X-direction and four spans in the Y-direction with the span lengths of 11.5 m and 10.4 m, respectively. Lateral bracing is chevron type in two first storeys and diagonal in the third one. The lateral load-resisting system for this structure is concentrically-braced frames with a seismic response modification coefficient, R, of 3.5. The yield stress of the steel material for all the steel parts is 235 MPa, with the 200,000 MPa modulus of elasticity. The structure had been designed with the aid of commercial engineering software, SAP, with the equivalent static force method applied for the seismic loading in design (see **Figure 6**).

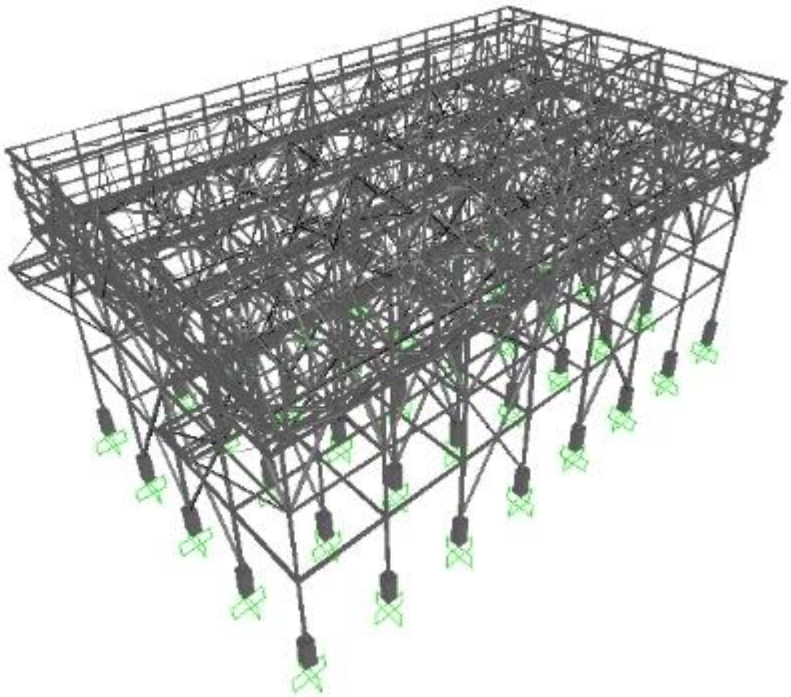
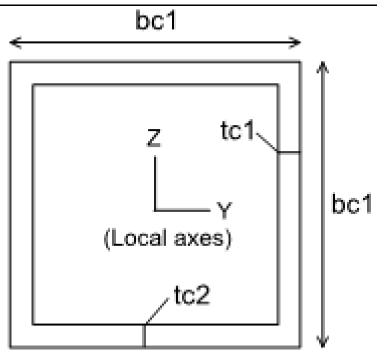


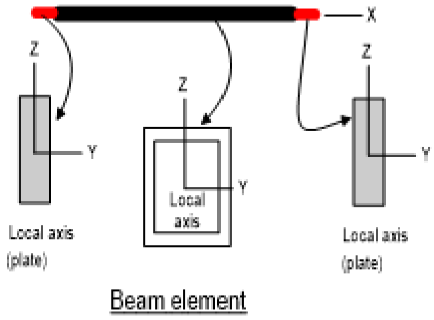
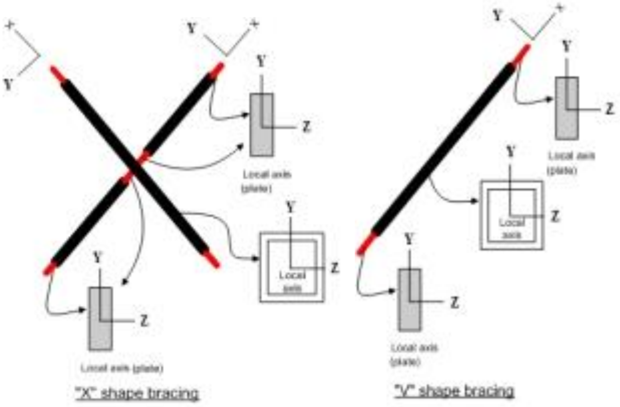
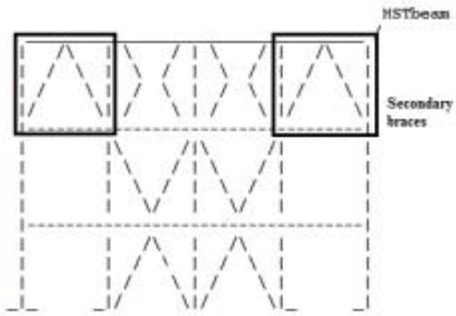
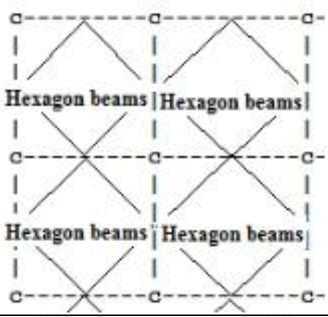
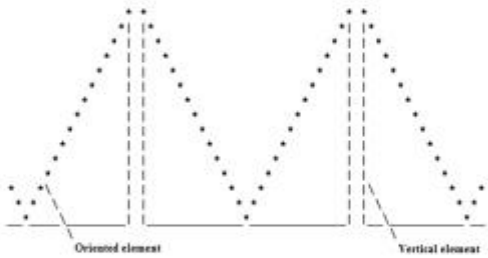
Figure 6. the steel ACC-model made in SAP for performing the elastic design.

5.1.1. OpenSees model description

The steel beams, except at the beam level, have box cross-sections and are attached to the box columns with simple plate connectors. The braces are also box profiles with plate connectors at their two ends. The braces, except for the main ones, installed at the third storey (known as collector elements or secondary braces) are truss elements. The hexagon beam elements situated at the roof are trusses with I-shape sections, similar to the V-frame members. The longitudinal elements connecting the V-frames at their top are made of the same section as V-frames. Lastly, the pyramid-shaped lateral bracings are truss elements with the steel pipe section. A summary of model components' sectional properties has been given in **Table 2**.

Table 2. Cross-sectional properties of the components of Tous' steel ACC.

Model element	Element configuration	Cross-section, mm
Column		Box 315×315×20 Box 250×250×20

Model element	Element configuration	Cross-section, mm
Beam		Box 244×244×12 Box 280×280×15 I 420×280×15×12
Brace		Box 250×250×20 Box 240×240×15
Secondary brace		Box 240×240×15
Hexagon beam		I 300×160×10×8
V-frame		I 180×180×12×6 I 180×180×8×6

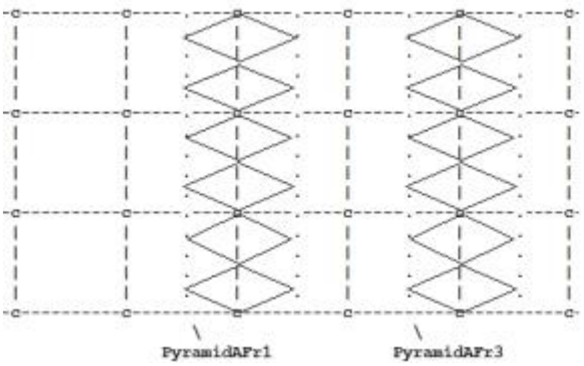
Model element	Element configuration	Cross-section, mm
Pyramid truss		Pipe 219.1×10

Table 2. (*Continued*)

Given the aim of numerical models to capture the realistic behaviour of ACC structures, material nonlinearities are incorporated in the model, wherever required; in other regions, elements with elastic behaviour are assented to. The steel columns are made of beam column elements with plastic hinges allocated at their ends with Steel02 material; beams are nonlinear elements with Steel02 material; braces, as well as pyramid trusses, are nonlinear Steel02. The strain hardening ratio is considered equal to 0.25, and the values recommended by the OpenSees software manual are used to define the gradual yielding portion of the Steel02 material model, i.e., R0=15, cR1=0.925, and cR2=0.15. The final 3D model constructed in OpenSees is demonstrated in **Figure 7**.

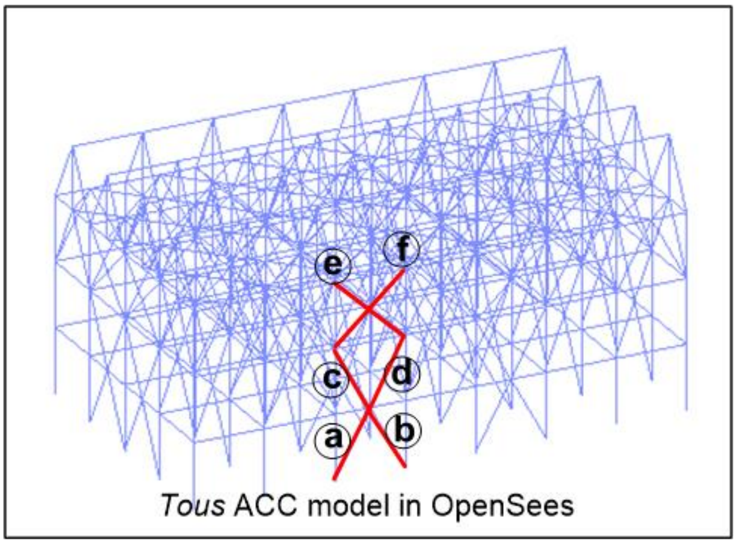


Figure 7. The 3D view of Tous' steel ACC structural model in OpenSees program.

5.1.2. Analysis and results of numerical simulation

The load for seismic analyzing was a strong ground motion (i.e., El-Centro ground motion record) scaled to the Tous city's design elastic response spectrum in the range of the structure fundamental period (see **Figure 8**). The scale factor of 1.40 was obtained after matching the earthquake record and the design response spectrums. **Figure 8** shows the axial force vs. deformation curves of the brace elements. Since the structure faced an actual seismic load, that is a ground motion without the seismic force reduction factor, the fuse elements began to display nonlinear behaviour, revealing itself as loops in hysteresis curves of the elements. The earthquake load was in X-direction (only one direction). **Figure 9** shows the base shear force vs. displacement curve of the ACC steel structure. As can be observed, the structure lateral displacement, measured at the roof level, is much less than the 2% critical inelastic drift. The 2% lateral drift limit can be derived from the H/200 (0.5%) allowable drift limit multiplied by the deflection amplification factor, C_d, of 4 for the intermediate moment-resisting frames as per the ASCE 7-16 code. An overall investigation of Tous' ACC reveals that, for a study at a numerical level, the designed ACC building has had proper seismic behaviour. Moreover, reading from Fig. 8, braces do not suffer great deformations or form significant force-displacement excursions perhaps due to the value of R-coefficient used in the ACC design; this finding is also in accordance with the observed not-significantly high value of the ultimate lateral drift.

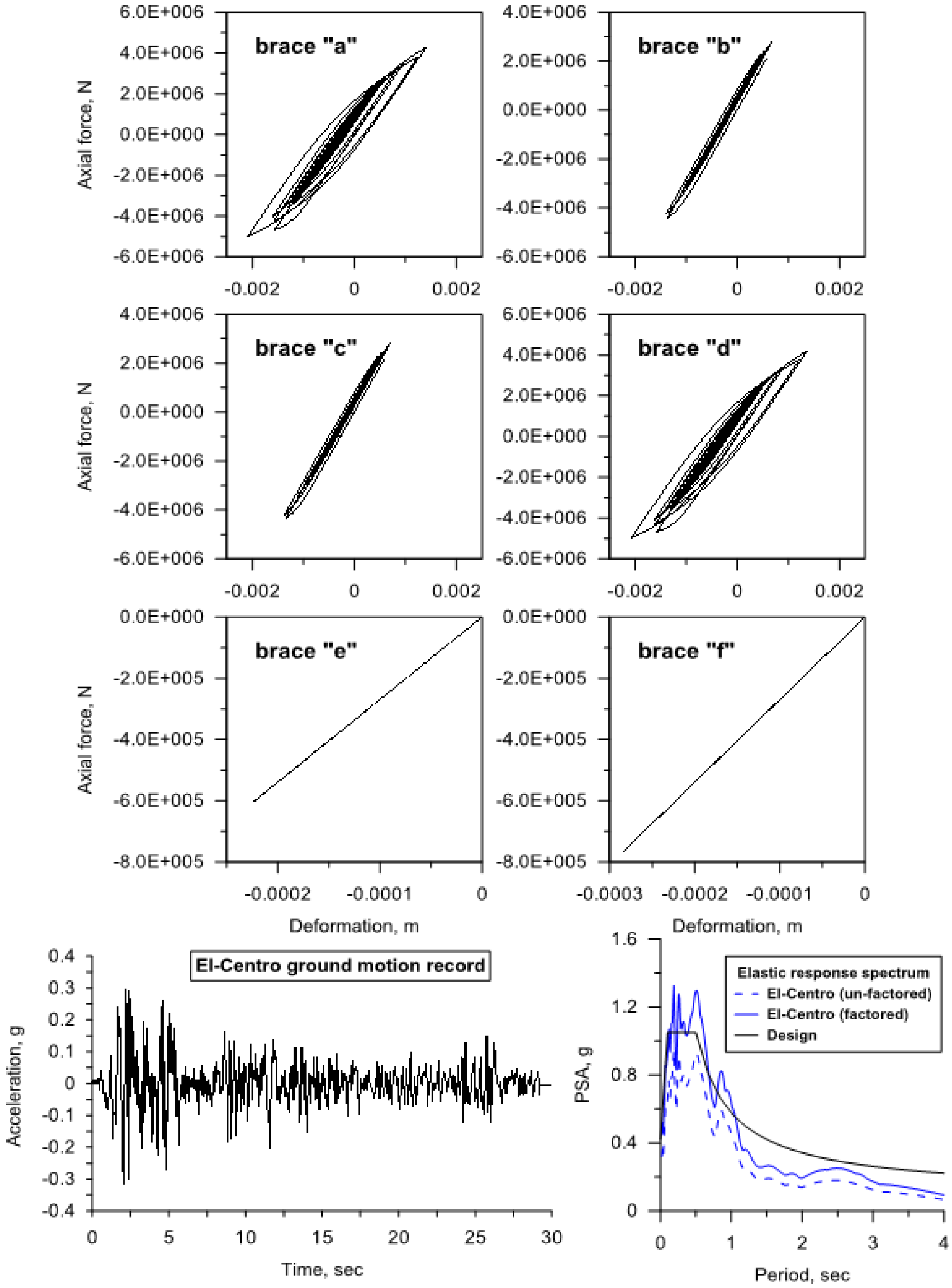


Figure 8. Axial force vs. deformation curves of Tous' ACC's various steel braces.

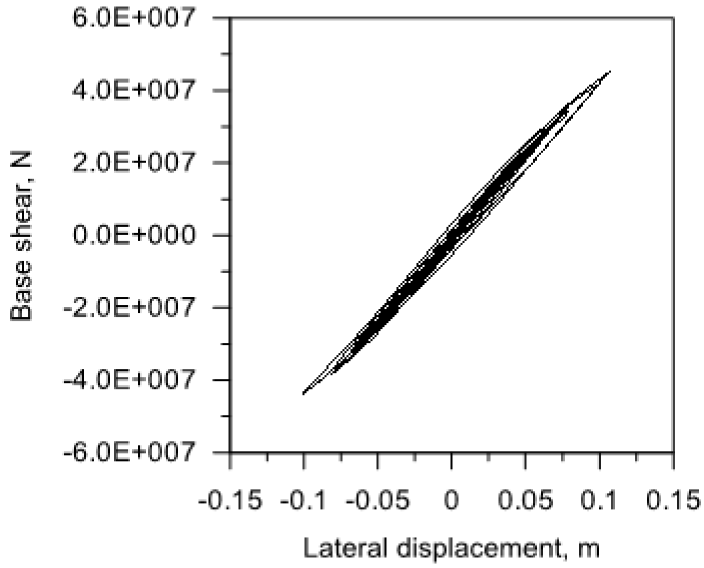


Figure 9. Base shear force vs. lateral displacement curve of Tous' ACC structure for earthquake in X-direction (displacement is measured at the roof level).

5.2. Chābahār's concrete-built ACC

Chābahār's ACC building is concrete built with a cantilevered-roof (see **Figure 10**). It has a 23.7 m length span in the X-direction and a 24.6 m length span in the Y-direction. The number of spans is 3.5 in the X-direction with one span in the direction of Y. The roof rests on the columns at +27.4 m height above the foundation level. The lateral force-resisting system of ACC is a concrete moment frame with a seismic response modification coefficient, R, of 5 selected for the design. The concrete compression strength is 28 MPa with the modulus of elasticity of 22,940 MPa, and the reinforcement-rebar yield stress is 400 MPa.

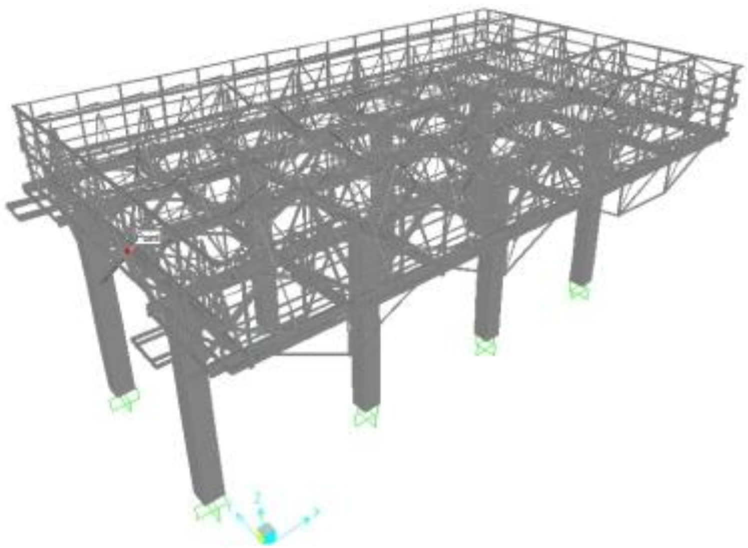
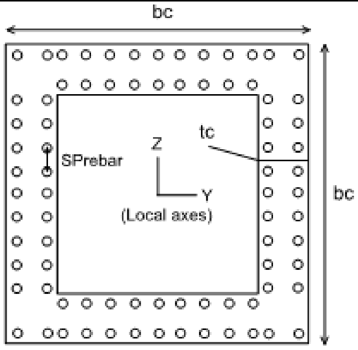
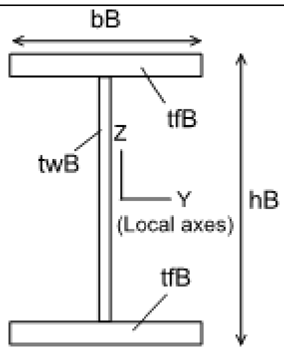
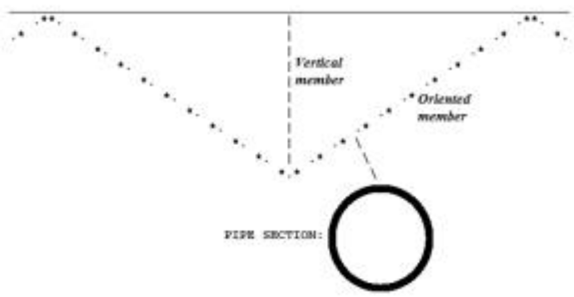
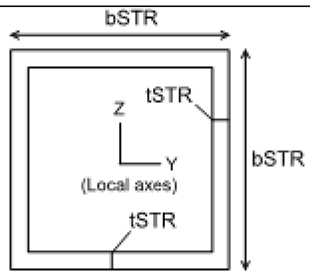


Figure 10. The concrete ACC-model in SAP software for conducting elastic design.

5.2.1. Model description

The reinforced concrete hollow box columns are composed of plain concrete and vertical re-bars. Steel beam elements are placed at the beam level with an I-shape cross-section. Steel collectors are steel truss elements supporting the roof. Hanging steel braces are positioned beneath the roof beams at the intermediate spans and shape a triangular form structure; hanging braces are steel pipe members. Hexagon elements at the roof are trusses with I-shape section. As well, V-frame members are trusses with I-shape sections. The longitudinal elements have identical sections with V-frames. The pyramid-shaped lateral bracings are truss elements with steel-pipe section. A summary of model elements configuration and properties is given in **Table 3** and demonstrated in **Figure 11**. The nonlinear components of the ACC include the following: concrete columns are beam column elements with plastic hinges at their ends; the concrete is Concrete02 material (E_c=22,940 MPa, f_{pc}=-28 MPa, f_{pcu}=-17 MPa, epsU=-0.0045, f_t=2.3 MPa, and E_{ts}=1,586 MPa) and the steel re-bar is steel hardening material, capable of nonlinear deformations (F_y=400 MPa and the hardening modulus of 0.125). The roof beams and collectors as well as pyramid braces are Steel02 material (E_s=200,000 MPa, F_y=235 MPa, b=0.25, R0=15, cR1=0.925, and cR2=0.15). Other structural elements, such as V-frames, hanging braces, and hexagon beams, are elastic (E_s=200,000 MPa).

Table 3. Cross-section properties of components of Chābahār's concrete ACC.

Model element	Element configuration	Cross-section, mm
Column		C 2160×2160×300
Beam		I 1250×450×30×12
Hanging steel brace		Pipe 273×11 Pipe 355.6×12.5
Collector		Box 550×25

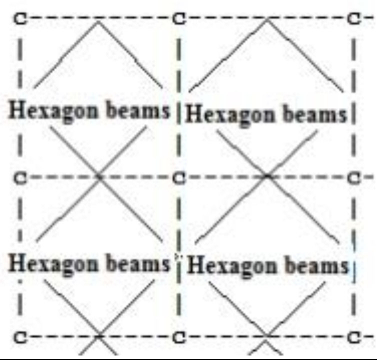
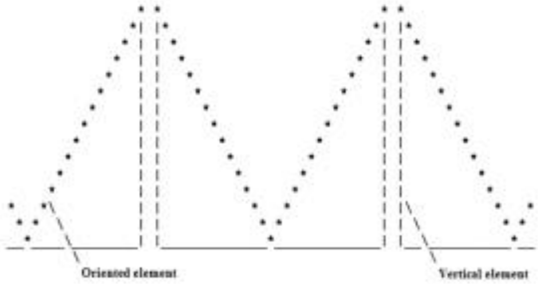
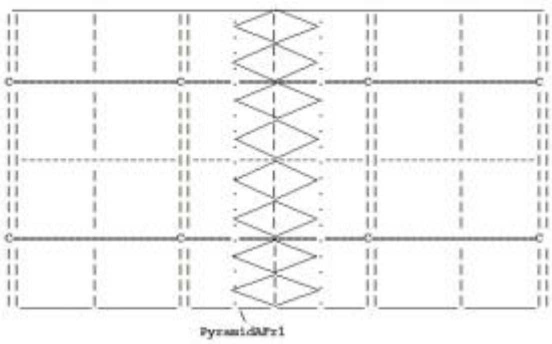
Model element	Element configuration	Cross-section, mm
Hexagon beam		I 320×180×12×8
V-frame		I 180×180×12×6 I 180×180×8×6
Pyramid truss		Pipe 219.1×10

Table 3. (*Continued*)

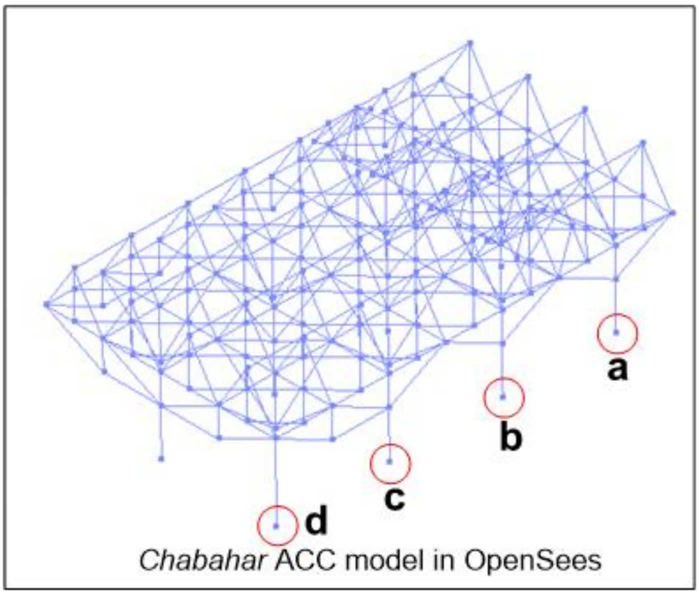


Figure 11. 3D model of Chābahār's ACC structure generated in OpenSees program.

5.2.2. Numerical results

The structure model is analyzed under the strong ground motion of El-Centro, visually scaled to the Chābahār design response spectrum using a 2.30 scale factor. It is worth to note that the discrepancy between the two applied scaling factors (i.e., 1.4 versus 2.3) is due to the difference of the ACCs' locations as well as their fundamental periods around which the ground motion response spectrum has been scaled to. **Figures. 1**2 and **13** show moment vs. rotation graphs for column and roof-beam elements of the ACC structure, respectively, for the earthquake load acting in the X-direction. As can be seen in **Figure 12**, concrete columns experience relatively great deformations (i.e., rotations) at their bottom section where the formation of plastic flexural hinges is expected (see **Figure 1(b)**). The earthquake inertia energy is dissipated via the inelastic force-deformation loops. The inelastic excursions developed steadily without any significant strength degradation or abrupt decline of capacity during the imposed earthquake, proving the fact that fuse elements operated properly in this concrete ACC structure. Given the structure symmetry in the X-direction, results for only half of the columns are presented herein.

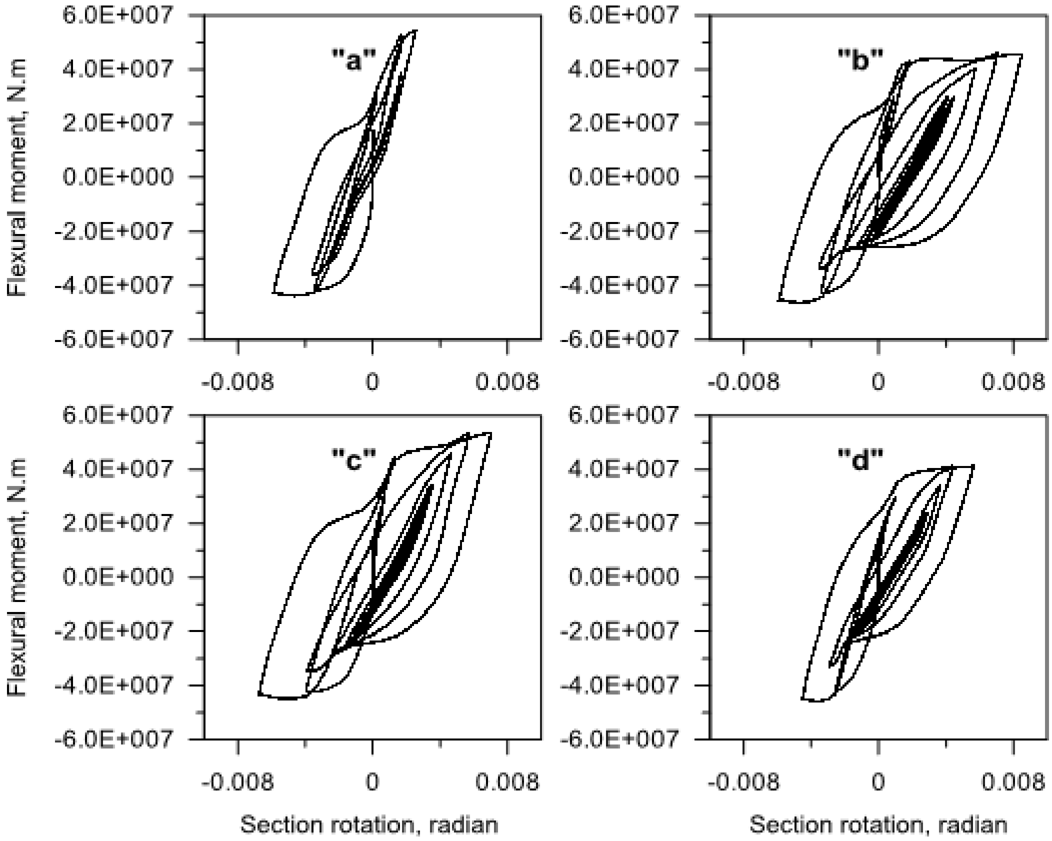


Figure 12. Moment vs. rotation curves of Chābahār's ACC columns at the column base.

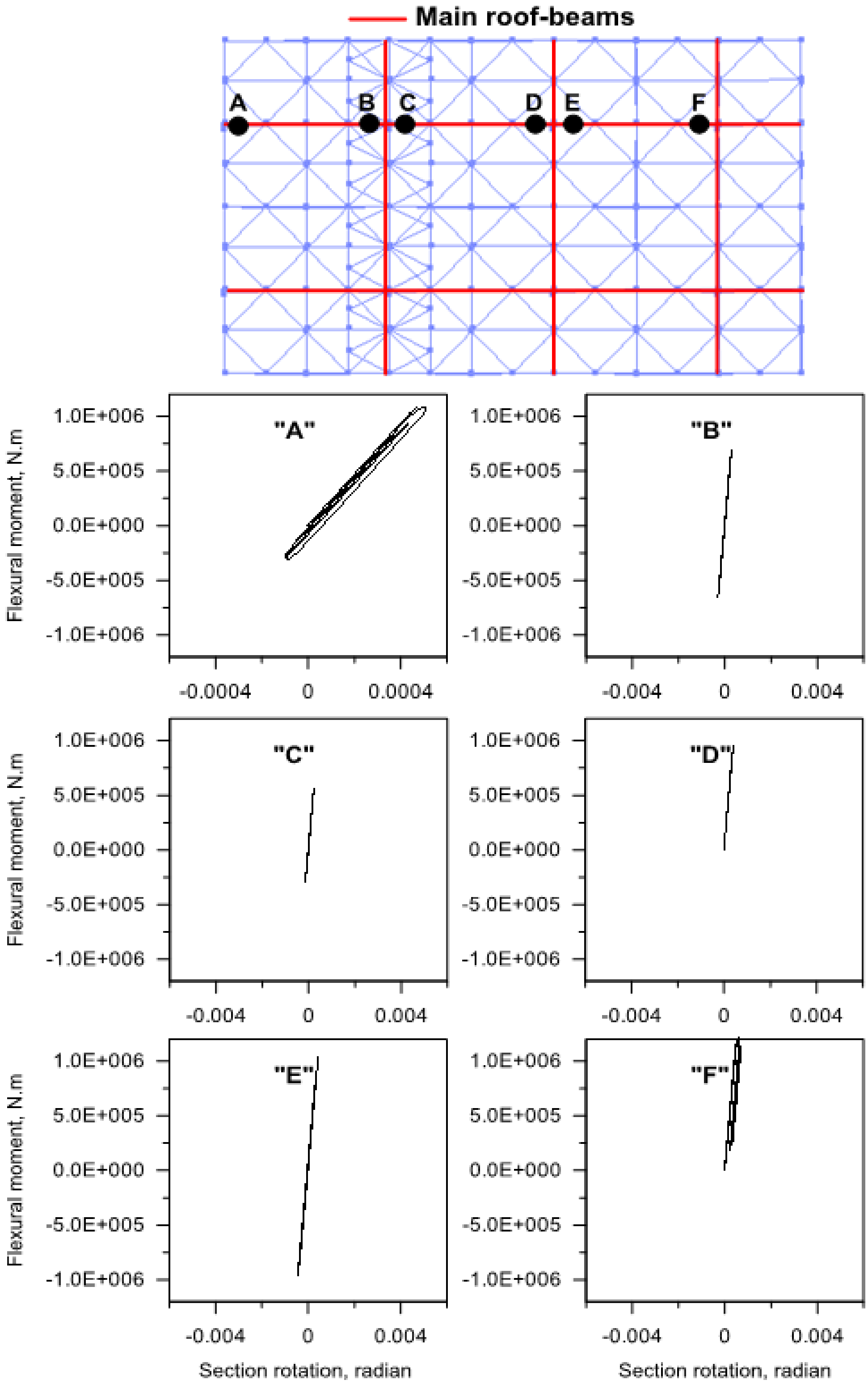


Figure 13. Moment vs. rotation curves of Chābahār's ACC roof beams.

Figure 13 shows that the roof beams remain elastic, while some bear small amounts of nonlinearity in their section. This seismic behaviour is actually expected from concrete ACCs in real strong seismic events. Reading from **Figures 12** and **13**, it is also evident that the ACC building model behaved according to the predicted behaviour or, in other words, the predictions have been correct given the results of numerical simulation. Looking at the general behaviour of the model and inspecting the model's overall stability, base shear vs. lateral displacement is drawn in **Figure 14** for the earthquake in the X-direction. It can be seen that the lateral displacement is much smaller than the suggested 2%~2.5% inelastic drift limit and therefore no failure is expected to occur during a strong earthquake according to the modeling results.

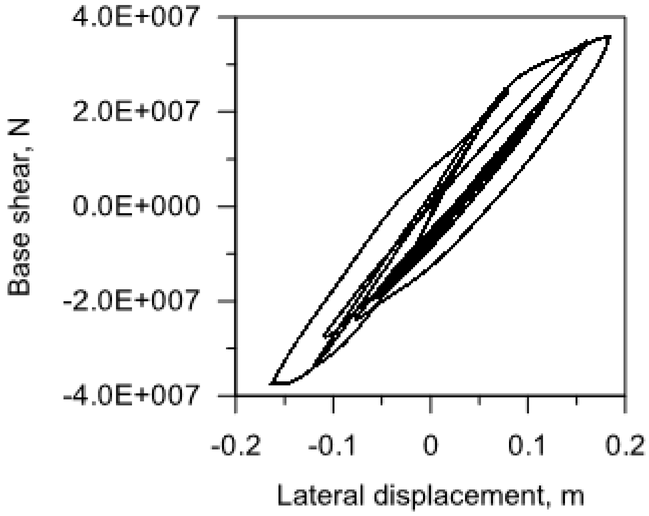


Figure 14. Base shear vs. lateral displacement curve for an earthquake in the X direction for Chābahār's ACC (displacement is measured at the roof level).

6. Conclusion

Numerical models and the associated computer programs provided in OpenSees software for the purpose of investigating the seismic behaviour of different types of ACCs were able to generate ACC structure models after defining minimum necessary input data by the analyst. In addition, any type of ACC structure within the domain of the program applicability can be easily modeled and dynamically analyzed by it. Two real industrial structures were probed into in order to verify the program ability as well as to investigate the seismic performance of the ACCs – as a complex structural system – more accurately for the first time. The models were created successfully and the results of numerical simulation fulfilled the expectations. This work thus succeeded in development of an OpenSees-program-based platform with the purpose of conducting the nonlinear dynamic time-history analyses of typical ACC structures, namely concrete- and steel-built ACCs. Beside observing the ACCs' seismic behaviour during strong ground motions, the seismic force modification coefficient, R, of the concrete and steel ACC structures could also been validated (R=3.5 for the steel braced and R=5 for the concrete moment framed ACCs), motivated by the fact that this seismic design information was deemed to be long-time debated within the engineering community. Further development of the program is plausible, for example, by including soil in the models and therefore possibly accounting for the soil-structure interaction in the case of seismic events.

Conflict of interest

The authors declare no conflict of interest.

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