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# Endurance time method in the linear seismic analysis of shell structures

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***Abstract***

*Endurance Time (ET) method is a response history based analysis procedure that can be used for estimating the seismic response of structures at different excitation levels in each response history. This seismic analysis method utilizes specific intensifying acceleration functions to analyze seismic behaviors. One of the potential applications of the ET method is in the seismic assessment of shell structures. In this study, a procedure for linear seismic analysis of shell structures is proposed and applications of this method is investigated for several cases of shell structures. These structures are analyzed under three ET acceleration functions in one direction and the results are compared to time history analysis considering seven actual earthquake records. Moreover, the results of the ET method are compared to response spectrum analysis method. The outcomes of the study reveal that the ET method predicts the linear seismic performance of shell structures with acceptable precision and significant reduction in analysis time. Furthermore, it is conluded that scattering of results of three ET analysis is very low and one analysis can be used instead of three. Finally, the comparison between THA and RSM results verify that response spectuarm method is a conservative method which occasionally encounters problems to evaluate bending stresses of shell structures.*

*Keywords: Endurance time method; Shell structures; Time history analysis; Response spectrum analysis*

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## 1. Introduction

With the improvement of computer capabilities for complex computations, structural engineers can model complex structures and their loadings more realistically. So that, time history methods that generate more accuracy compared to simple methods, are developed to predict seismic behaviour of sturctures. Since the time history methods are in a time domain, they can assess seismic behaviour of structures during earthquakes durations. Among different methods of time history analysis, the standard one is widely employed by professionals. In this method, several real scaled accelograms apply to structures and then the structures are analyzed under this time history loadings. This method possesses high accuracy but due to time-consuming feature of this method, in several cases, it is impossible to apply. Due to impossibility of the aforementioned method in more complex structures, a new technique for time history seismic assesment of structures is developed. In this approach, the structure is subjected to accelerograms that impose increasing dynamic demand on the structure with time[1]. This method is called Endurance Time or ET.

The Endurance Time(ET) method is a new developed technique that can be employed in linear and nonlinear analysis of structures under earthquake loads. One of the major benefits of the ET method over standard time history analysis is reducing the time of analysis with minimum loss of accuracy. In the ET method similar to standard time history analysis, the changes of response of a structure can be plotted versus time[1].

Shell structures are widely utilized to construct many structures such as roof, domes, cooling towers, silos, tanks, chimneys and other similar structures. In a number of cases, it is difficult to construct shell structures; however if this constraint can be overcome, they provide a natural choice for many applications [2]. A number of serious failures of shell structures during have led to significant researches into their behaviors, analyses and designs [3, 4, 5]. One of the loadings that could cause failure in shell structures is earthquake loading. There are several methods for evaluating seismic

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behavior of shells such as equivalent static analysis method, response spectrum analysis method, time history analysis method and other related methods [6].

In this paper, application of the ET method to linear seismic analysis of shell structures is investigated. This method is verified in various cases of different structures. By the way, due to many special particularities in dynamic analysis of shells such as involvement of complex mode shapes, seismic analysis of shell structures with ET method deserve a separate and independent study. Another aim of this research is to lay the foundation for nonlinear applications in seismic assessment of shell structures where true benefits of an elaborate response history analysis can be realized. Six shell structures including two domes, two half-cylinder roofs and two cooling tower hyperbola shells are analyzed under ET acceleration functions in one direction and results are compared to time history Analysis considering seven actual earthquake records. Furthermore, the results of THA method are compared to response spectrum analysis method using design spectra [7].

## 2. Concept of endurance time method

Enduranse time method is a new dyanmic time history based analysis method. In this method, structures are subjected to a increasing dynamic excitation against time. The response of structures during time can be observed and the maximum response corresponding to different level of excitation can be investigated[1].

The concept of ET method can be explained properly with a hypothetical experiment. It is assumed that three structures with indeterminate characteristics are placed on the shaking table. It is presumed that shaking table is subjected to a random vibration that its intensity increases gradually. In the beginning of experiment and during small-amplitude vibrations, all of three structures are stable. Next, it is assumed that with elapsing the time and intensifying excitation level, at first structure no. 1 (for example in t=10sec) and then structure no. 2 (for example in t=15sec) and finally structure no. 3 (for example in t=20sec) are collapsed. By implementing this simple experiment, it can be concluded that structure no.1 that has the minimum enduranse time, further has weaker performance and structure no.2 has stronger performance among these three structures [1,8,9].

If applied dynamic excitation is corresponded to dynamic excitations due to earthquake records, it can be expected that structure no. 2 would be more resistant against seismic excitation compared to structure no. 1. On the other hand, by implementing this test, we can estimate seismic performance of different cases. In the endurance time method, these simple consepts are employed to develop an applicable analysis tool in order to assess seismic behaviour of structures. In the ET method, structure is imposed under increasing accelogram and the maximum response parameters are ploted versus time. Based on the requirements, these parameters may include a series of performance criteria which are used to analyze and design such as displacements, forces, stresses and other related parameters.

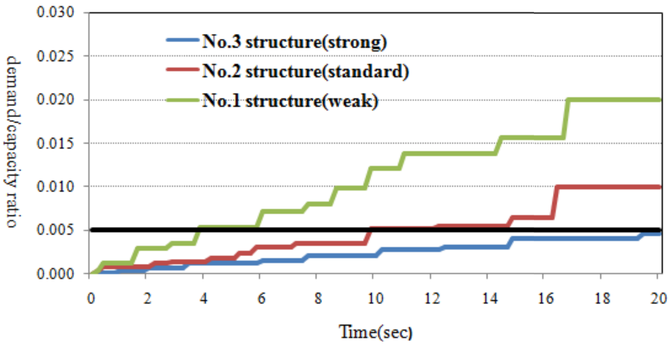


**Fig. 1.** Determination of weak, standard and strong structures with concept of target time

Figure1 illustrates schematic application of the ET method. If it is considered that the ultimate demand/capacity limit ratio is equal to 1, the maximum time which structure response attains the ultimate demand/capacity limit ratio can be extracted (or the maximum time that structure can endure). It can be observed in figure 1 that endurance time for structure no. 1 is 4 sec, for structure no. 2 is 10 sec and for structure no.3 is 20 sec. If it is assumed that this accelogram in 10th second is corresponding to intensity of design earthquake spectrum, it can be proceeded to evaluate the considered structures[10]. In this example, structure no.1 reaches the maximum of its capacity before the required time (10th sec); therefore this structure do not satisfy the design criteria and is weak. structure No. 2 reaches maximum of its capacity after 10th sec; therefore this structure satisfy design criteria and is standard. Moreover, structure no. 3 reaches its maximum capacity at a later time compared to the minimum required time, thus this structure is strong.

## 3. ET acceleration functions

To generate the endurance time (ET) acceleration functions, a random vibration accelerogram similar to a white noise which was modified by a filter in the frequency domain is primarily used. The resulting stationary accelerogram is then modified by applying a linear profile function that forces it to intensify with respect to peak accelerations at different time intervals. These accelerograms function effectively to fulfill the objective of demonstrating the concept of ET analysis applied in both the linear and nonlinear seismic analysis of structures [11]. For this purpose, acceleration response and target displacement response of the ET accelerogram is defined by Eq. (1) and Eq. (2), respectively:

$$S_{aT}(T,t) = \frac{t}{t_{Target}} S_{aC}(T) \qquad (1)$$

$$S_{uT}(T,t) = \frac{t}{t_{Target}} S_{aC}(T) \times \frac{T^2}{4\pi^2} \qquad (2)$$

where $S_{aT}(T,t)$ and $S_{uT}(T,t)$ is the target acceleration response and target displacement response at time t respectively , $T$ is the period of free vibration and $S_{aC}(T,t)$ is the design acceleration spectrum [9]. Analytical approaches to find an accelerogram which satisfies the target response defined by

Eqs. (1) and (2) are formidably complicated [12]. For production of the second generation of ET functions, an optimization method with target function is applied as below:

$$\min F(a_g)=\int_0^{T_{max}}\int_0^{t_{max}}\left\{\left[S_a(T,t)-S_{aT}(T,t)\right]^2+\alpha\left[S_u(T,t)-S_{uT}(T,t)\right]^2\right\}dt\,dT \tag{3}$$

Where $a_g$ is the desired ET accelerogram and $\alpha$ is an optimization weighting parameter. A typical ET accelration function is illustrated in figure 2 [12].

## 4. Shell structures models

To compare the shell structures seismic responses under endurance time accelograms by standard time history method, six shell structures are considered. The first two structures are hemisphere dome shells, other two shell structures are horizontal half-cylinders and the last two shell structures are hyperbola cooling tower shells that their characteristics is given in table 1.

All six shell structures are modeled with finite element method and all their materials are linear elastic with modulus of elasticity equal to 28000 Mpa. As far as these three identical pairs, finite element model of each considered pair of structure is shown in figure 3.

## 5. Selection of records and ET accelaration functions

In this study, shell structures are analyzed under seven one-horizontal component of actual ground motion records in order to compare the result with the ET method and response spectrum analysis. All of the accelogram are selected from peer database on soil condition C [13]. To analyze response spectrum and to scale earthquake records, a spectrum with coeficients given in 2 based on ASCE/SEI 7-05 is considered [14]. To select earthquake records, code requirements of FEMA 440 for soil condition C are satisfied [15]. In addition in table 3, characteristics of seven selected actual records are presented. The average response spectrum of seven ground motions, which are scaled according to ASCE/SEI 7-05 code requirements are illustrated in Figure 4 for T = 0.25 sec and $\xi = 0.05$.

presently, several ET acceleration functions are available which depending on problems, one of these ET records can be used to anlyze different structures. In this research, IN series of the ET functions (ETA20inx01, ETA20inx02 and ETA20inx03) are used [16]. To accomplish this task, ten seconds of x-component of the aforementioned ET functions are considered and response spectrum is plotted for them. Subsequently, the average of the obtained spectrums are scaled to the desired design spectrum according to ASCE/SEI 7-05 code requirements. The scaled x-components of IN series for $T = 0.25$ s and $\xi = 0.05$ are illustrated in figure 5.

**Table 2.** characteristics of selected design spectrum based on ASCE/SEI 7-05 code

| Site | $s_1$ | $S_s$ | $F_v$ | $F_a$ | $S_{DS}$ | $S_{D1}$ | $T_0$ | $T_s$ |
|---|---|---|---|---|---|---|---|---|
| C | 0.75 | 1.65 | 1.3 | 1.0 | 1.1 | 0.65 | 0.12 | 0.59 |

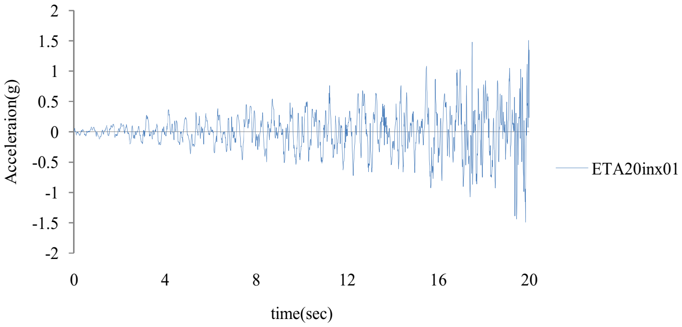


**Fig. 2.** A typical ET accelration function

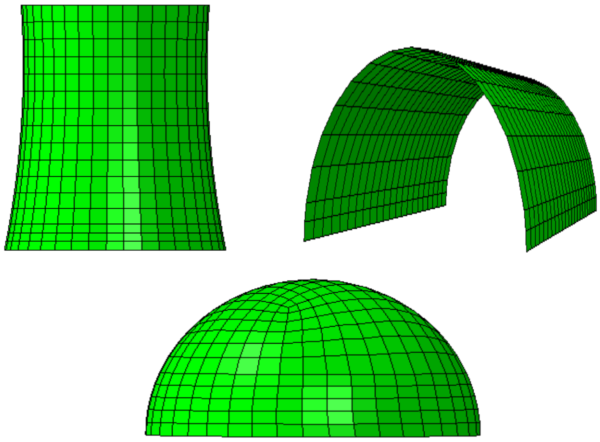


**Fig. 3.** Finite element models of one of each considered shell structures

**Table 1.** characteristics of 6 considered shell structures

| ID | type | Height(m) | Height from Throat to top(m) | Length(m) | Base circle diameter (m) | Throat circle diameter (m) | Top circle diameter (m) | Thickness |
|---|---|---|---|---|---|---|---|---|
| D1 | dome | 5 | - | - | 10 | - | - | 0.2 |
| D2 | dome | 10 | - | - | 20 | - | - | 0.3 |
| R1 | half-cylinder roof | 7.5 | - | 30 | 15 | - | - | 0.3 |
| R2 | half-cylinder roof | 10 | - | 40 | 20 | - | - | 0.25 |
| C1 | Cooling tower hyperbola shell | 93.6 | 23.5 | - | 58 | 50 | 51 | Variable (1.3 at bottom, 0.32 at h=10m and 0.18 at h=30m to top of tower) |
| C2 | Cooling tower hyperbola shell | 76 | 20 | - | 72.2 | 60 | 61.4 | Variable(1.2 at bottom, 0.22 at h=10m and 0.18 at h=24m to top of tower) |

**Table 3.** Characteristics of seven actual erathquake records

| Record ID | Event | Year | M | R (km) | PGA (g) - major | Station | Soil | Mechanism |
|---|---|---|---|---|---|---|---|---|
| TABAS/DAY-LN | Tabas | 1978 | 7.35 | 13.94 | 0.328 | 9102 Dayhook | C | reverse |
| LOMAP/STG | Loma Prieta | 1989 | 6.9 | 13.0 | 0.512 | Saratoga - Aloha Ave | C | reverse-oblique |
| IMPVALL/H-PTS | Imperial Valley | 1979 | 6.5 | 14.2 | 0.204 | Parachute Test Site | C | strike-slip |
| WHITTIER/A-ALH | Whittier Narrows | 1987 | 6.0 | 13.2 | 0.414 | Alhambra, Fremont Sch | C | reverse-oblique |
| NORTHR/CCN | Northridge | 1994 | 6.7 | 25.7 | 0.256 | LA - Century City CC North | C | reverse |
| CHICHI/CHY | Chi-Chi, Taiwan | 1999 | 7.6 | 15.3 | 0.277 | CHY029 | C | reverse-oblique |
| NORTHR/ORR | Northridge | 1994 | 6.7 | 22.6 | 0.568 | Castaic - Old Ridge Route | C | reverse |

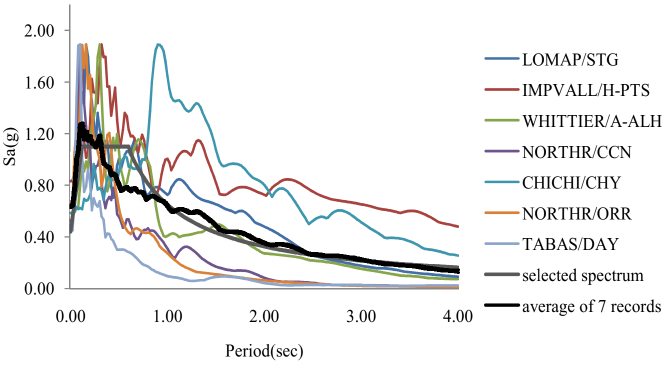


**Fig. 4.** Scaling earthquake records according to ASCE/SEI 7- for T= 0.25s and ξ=0.05

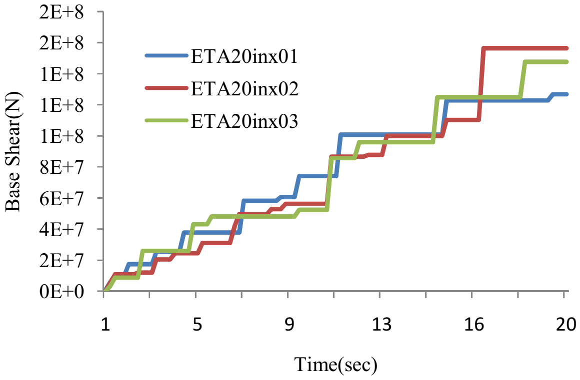


**Fig. 6.** ET diagram of base shear in C1

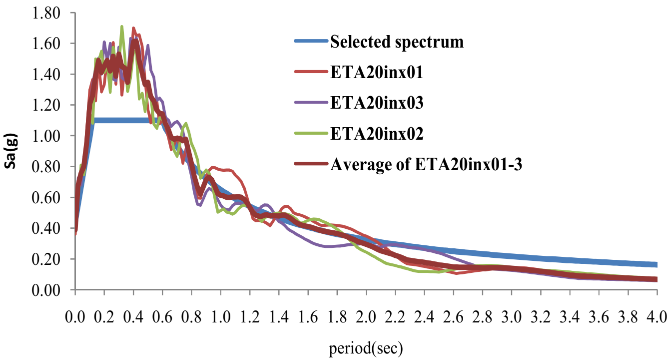


**Fig. 5.** Scaled x-components of IN series of ET functions for T=0.25s and ξ=0.05

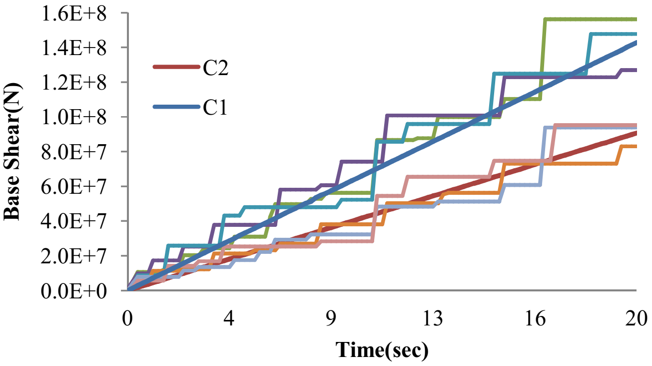


**Fig. 7.** Average of ET diagram for base shear in C1 and C2 shells

## 6. Results and Discussion

### *6. 1. Analysis Results*

In the ET method, the response of structure history outputs are presented as the maximum absolute value of the considered variables from $t$ = 0 up to $t$ = 20 sec. The ET diagrams for base shear responses of C1 shell is shown in Figure. As can be observed, in general, most responses increase in a nearly linear manner according to the rate of excitation intensification versus time. As can be illustrated in figure 6, it is evident that for each one of the three ET function the results are nearly the same. In addition, it can be fitted a line to each one of the ET digrames that shows the ET response in every time. In figures 7 to 9, the averages of these

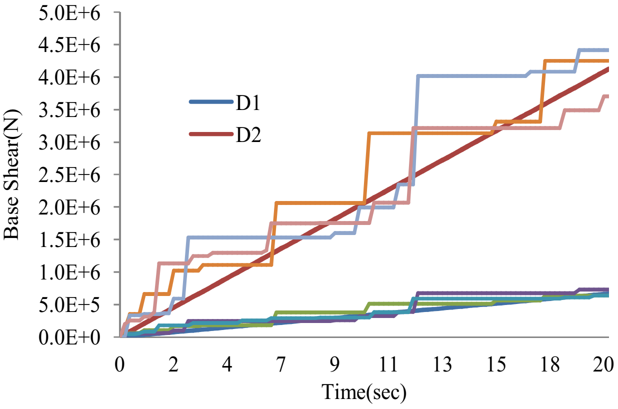


**Fig. 8.** Average of ET diagram for base shear in studied domes

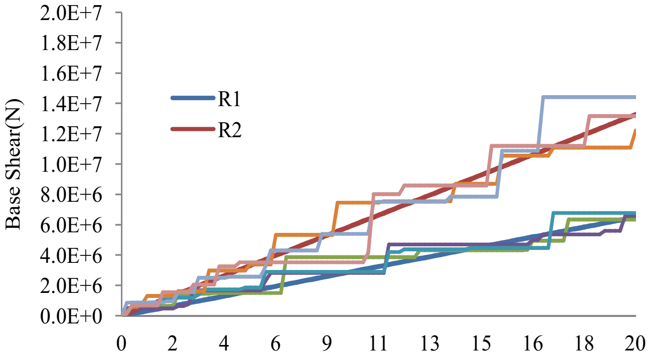


**Fig. 9.** Average of ET diagram for base shear in studied half-cylinder roofs

lines are drawn for all the studied shells from $t = 0$ to $t = 20$ sec. (the average of three selected ET functions)

Tables 4 and 5 summarize the results of analyses of C1 subjected to the earthquake records and the ET acceleration functions, respectively. As can be seen, standard deviation of the results in the ET is lower than THAs. Moreover in tables 4 and 5, the maximum membrane and bending of meridional and hoop stresses are presented, because this stresses play specific role in design of cooling tower shells.

Table 6, 7 and 8 present the seismic analysis results of the shell structures. The average difference which is presented in this table derives from Eq. (4).

$$Average\ Difference = (V_{ET} - V_{EQ}) / (V_{EQ}).\ 100 \qquad (4)$$

**Table 4.** Analysis results of C1 under seven scaled earthquake records

| | | | | | | |
|---|---|---|---|---|---|---|
| TABAS/DAY-LN | 41.0 | 17.2 | 5 | 1.2 | 1.67 | 0.8 |
| LOMAP/STG | 70.2 | 22.1 | 8.3 | 2.5 | 1.92 | 1 |
| IMPVALL/H-PTS | 68.5 | 18.9 | 5.6 | 2.64 | 1.6 | 0.6 |
| WHITTIER/A-ALH | 40.1 | 19.3 | 5.3 | 2.37 | 1.68 | 0.7 |
| NORTHR/CCN | 63.6 | 24.9 | 7 | 3 | 1.85 | 0.87 |
| CHICHI/CHY | 74.5 | 23.8 | 5.1 | 2.1 | 1.6 | 0.73 |
| NORTHR/ORR | 78.5 | 26.3 | 6.7 | 2.9 | 1.67 | 1 |
| Average | 62.3 | 22 | 6.1 | 2.4 | 1.7 | 0.8 |
| STDEV | 15.6 | 0.3 | 1.2 | 0.6 | 0.1 | 0.2 |

**Table 5.** Analysis results of C1 under 3 ET records(series in) until target Time(t =10sec)

| Record ID | Base shear (MN) | Displacement (top of tower)(mm) | Membrane meridional stress(MPA) | Bending meridional stress(MPA) | Membrane hoop stress(MPA) | Bending hoop stress(MPA) |
|---|---|---|---|---|---|---|
| ETA20inx 01 | 63.0 | 28 | 6.4 | 2.7 | 1.7 | 0.7 |
| ETA20inx 02 | 78.1 | 25 | 7.3 | 3.2 | 1.8 | 0.8 |
| ETA20inx 03 | 73.8 | 25 | 7.0 | 3.2 | 1.9 | 0.8 |
| Average | 71.6 | 26 | 6.9 | 3.0 | 1.8 | 0.8 |
| STDEV | 7.8 | 0.2 | 0.5 | 0.3 | 0.1 | 0.1 |

**Table 6.** Analysis results of studied domes

| Shell Structure | Seismic Analysis Type | Base shear(MN) | Displacement(top of shell)(mm) | Maximum membrane meridional stress(MPA) | Maximum bending meridional stress(MPA) | Maximum membrane hoop stress(MPA) | Maximum bending hoop stress(MPA) |
|---|---|---|---|---|---|---|---|
| D1 | Standard THA average | 0.37 | 4.1 | 0.57 | 0.36 | 0.27 | 0.12 |
| | ET average until t=10sec | 0.32 | 4 | 0.53 | 0.45 | 0.29 | 0.12 |
| | RSM | 1.1 | 7.3 | 0.67 | 0.34 | 0.37 | 0.14 |
| | Average difference between THA and ET(%) | -13.51 | -2.44 | -7.02 | 25 | 7.41 | 0 |
| | Average difference between THA and RSM(%) | 197.3 | 78.05 | 17.54 | -5.56 | 37.04 | 16.67 |
| D2 | Standard THA average | 2.25 | 16 | 1.03 | 0.65 | 0.5 | 0.21 |
| | ET average until t=10sec | 1.95 | 14 | 1.03 | 0.65 | 0.48 | 0.2 |
| | RSM | 7.08 | 38 | 1.5 | 1 | 0.65 | 0.25 |
| | Average difference between THA and ET(%) | -13.33 | -12.5 | 0 | 0 | -4 | -4.76 |
| | Average difference between THA and RSM(%) | 214.67 | 137.5 | 45.63 | 53.85 | 30 | 19.05 |

**Table 7.** Analysis results of studied half-cylinder roofs

| Shell Structure | Seismic Analysis Type | Base shear(MN) | Displacement (top of shell)(mm) | Maximum membrane meridional stress(MPA) | Maximum bending meridional stress(MPA) | Maximum membrane longitudinal stress(MPA) | Maximum bending longitudinal stress(MPA) |
|---|---|---|---|---|---|---|---|
| R1 | Standard THA average | 3.88 | 4.8 | 9.15 | 2.42 | 3.45 | 2.57 |
| | ET average until t=10sec | 3.38 | 4.4 | 8.63 | 2.21 | 3.25 | 2.1 |
| | RSM | 6.80 | 8.0 | 15.75 | 4.91 | 5.95 | 3.85 |
| | Average difference between THA and ET(%) | -12.89 | -8.33 | -5.68 | -8.68 | -5.80 | -18.29 |
| | Average difference between THA and RSM(%) | 75.26 | 66.67 | 72.13 | 102.89 | 72.46 | 49.81 |
| R2 | Standard THA average | 5.60 | 13.8 | 13.93 | 9.94 | 5.96 | 6.48 |
| | ET average until t=10sec | 5.90 | 15.7 | 15.89 | 11.03 | 6.55 | 6.78 |
| | RSM | 10.00 | 20.0 | 23.00 | 13.23 | 10.50 | 10.10 |
| | Average difference between THA and ET(%) | 5.36 | 13.77 | 14.07 | 10.97 | 9.90 | 4.63 |
| | Average difference between THA and RSM(%) | 78.57 | 44.93 | 65.11 | 33.10 | 76.17 | 55.86 |

**Table 8.** Analysis results of studied cooling tower hyperbola shells

| Shell Structure | Seismic Analysis Type | Base shear(MN) | Displacement (top of shell)(mm) | Maximum membrane meridional stress(MPA) | Maximum bending meridional stress(MPA) | Maximum membrane hoop stress(MPA) | Maximum bending hoop stress(MPA) |
|---|---|---|---|---|---|---|---|
| C1 | Standard THA average | 62.30 | 21.9 | 6.10 | 2.60 | 1.70 | 0.78 |
| | ET average until t=10sec | 71.60 | 25.4 | 6.90 | 3.02 | 1.80 | 0.81 |
| | RSM | 120.00 | 29.6 | 7.60 | 4.24 | 2.13 | 1.23 |
| | Average difference between THA and ET(%) | 14.93 | 15.98 | 13.11 | 16.15 | 5.88 | 3.85 |
| | Average difference between THA and RSM(%) | 92.62 | 35.16 | 24.59 | 63.08 | 25 29 | 57 69 |
| C2 | Standard THA average | 42.5 | 16.1 | 7.76 | 2.99 | 1.57 | 0.25 |
| | ET average until t=10sec | 45.3 | 18.3 | 7.34 | 3.32 | 1.53 | 0.27 |
| | RSM | 75.0 | 26.7 | 8.17 | 3.71 | 1.77 | 0.73 |
| | Average difference between THA and ET(%) | 6.59 | 13.66 | -5.41 | 11.04 | -2.55 | 8.00 |
| | Average difference between THA and RSM(%) | 76.47 | 65.84 | 5.26 | 24.08 | 12. 73 | 192.0 |

where $V_{ET}$ is the average of the maximum values obtained from the ET acceleration functions until the target time (10th second), and $V_{EQ}$ is the average of th maximum values obtained from the selected seven scaled earthquake records (THA). Furthermore, this procedure (Eq. (4)) is used to calculate the average difference between RSM method and THA responses. As indicated in tables 6, 7 and 8, in most cases, the difference percentages between the ET analysis and the THA are below 20%. The differences in responses between the two methods (the earthquake records and ET records) are justifiable taking differences in the spectral accelerations into consideration; however, these differences are reasonable considering the accidental nature of earthquake ground motions. These differences reveal the acceptable accuracy of using the ET records to evaluate the average results of actual earthquake records. In addition, it is evident that the results in RSM method are highly conservative and in comparing to the RSM method, the results of the ET method are closer to the THA results. In several cases, the RSM results are two or three times higher than the average of THAs.

### *6. 2. Comparing stress distributions in THA, ET and RSM method*

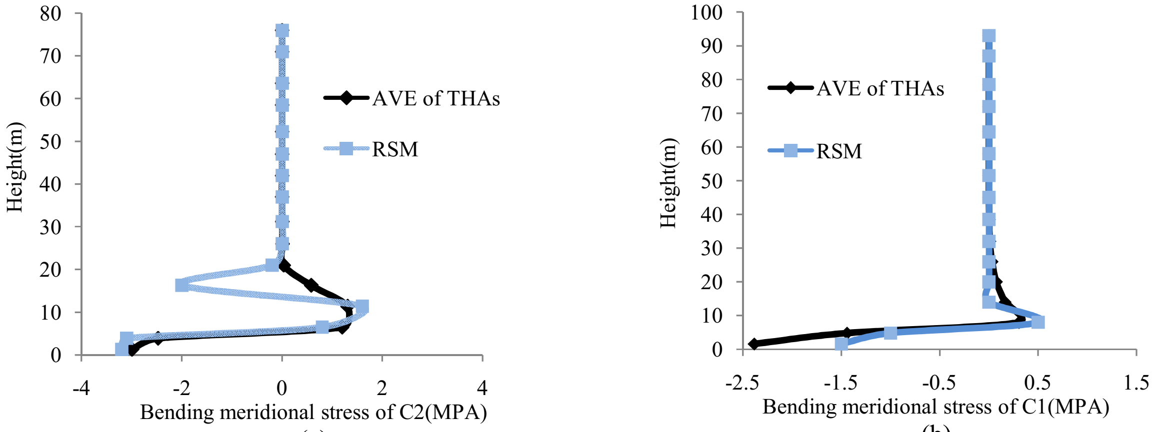
In this section, the accuracy of ET analysis and the RSM method in estimating the distribution of shell stresses are investigated. This is accomplished by drawing bending and membrane stresses at various elevations of shell structures in each three methods. A number of selected diagrams are shown in Figures 10 to 13. As can be expected, in seismic analysis of cooling tower and dome shells, meridional stress has higher magnitudes compared to hoop stresses and bending stresses affect local (bending stresses tend to zero with increasing in height of shells).

In general, the stress distributions resulted from the ETA and the THA procedures have reasonable consistency. This indicates acceptable level of precision achieved in evaluation of seismic responses of shells by the ET method and accurate selection of the target time. nearly in all shells, distribution of stresses in the RSM method reveal that this method is more conservative compared to the ET method; however in several cases, this method has problem to predict the bending stresses (for example figure 10). The results of ET analyses in the prediction of membrane meridional stresses of the C1 and R2 has minimum consistency among the cases under investigation with the THA (figures 11(a) and (b)), and in the domes and the R1 results of membrane stresses of the ET analysis are highly close to the THA (figures 12 and 13). In addition, the results of the RSM method in predicting meridional stresses of domes have reasonable accuracy (figures 12(a) and (b)).

### *6. 3. Estimating the maximum von-Mises stresses in the ET method*

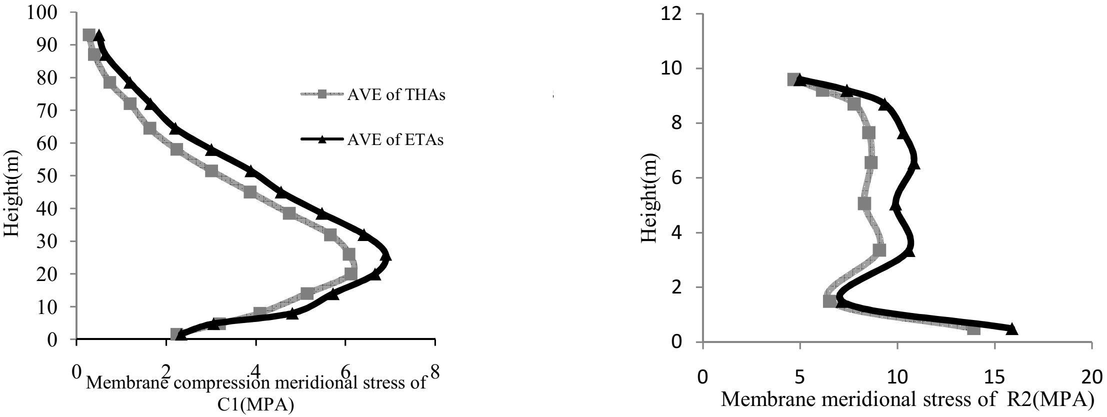
In this section, the precision of ETA estimations for evaluation of the maximum von-Mises stresses of the shell structures under study are investigated. For this purpose, correlation diagrams that explain the relation of von-Mises stress at all elements of shell structures are utilized. Theses diagrams are illustrated in figure 14.

As shown in figure 14, the maximum von-Mises stresses resulted from the average of ETAs have a reasonable accordance and correlation with the average of THAs. As can be seen in the demonstrated charts in figure 14, the trend lines which fitted on points in the diagrams are lying nearly on Y=X line. This indicates that stress estimations in two methods have satisfactory level of consistency. As can be seen in figure 14, the ETA estimations in C1 are usually higher than those by the earthquake records, and in R1 and two the domes under study are usually lower than those from the analysis by actual earthquake records. Further in the R2, the ETA results have highly reasonable consistency with the THA. Moreover, the compatibility of the results in near the base elements of domes is lower compared to other elements of domes and this has led to a significant reduction in the ETA and THA consistency in domes under investigation (figures 14 (e) and (f)).



(a) (b)

**Fig. 10.** Bending meridional stress of C1 and C2 shells



(a) (b)

**Fig. 11.** Membrane meridional stresses of C1 and R2

## 7. Conclusion

Due to time-consuming of analysis of shell structures under actual earthquake motions, it is necessary to develop new time history methods which prescribe seismic responses of shell structures with reasonable accuracy. In this study, six different shell structures including two domes, two half-cylinders and two cooling tower hyperbola shells are considered.

All these structures are analyzed under seven earthquake records and three ET functions. It is revealed that the ETA method properly evaluates membrane, bending and von-Mises stresses of the shells under investigation; however, this method occasionally cannot predict von-Mises stresses of near base elements of shells as well as other elements. In addition, it is verified that scattering of the results of three ET analyses are highly low and one analysis can be used instead of three. Consequently, it is concluded that the ET method can predict linear seismic responses of shell structures with acceptable accuracy and significant reduction in computational efforts compared to the THA. Moreover, the results of standard THA are compared with the RSM method. This comparison displays that nearly in all cases, the RSM method conservatively predicts seismic responses of shells; however in several cases, this method has problem to evaluate the bending stresses.

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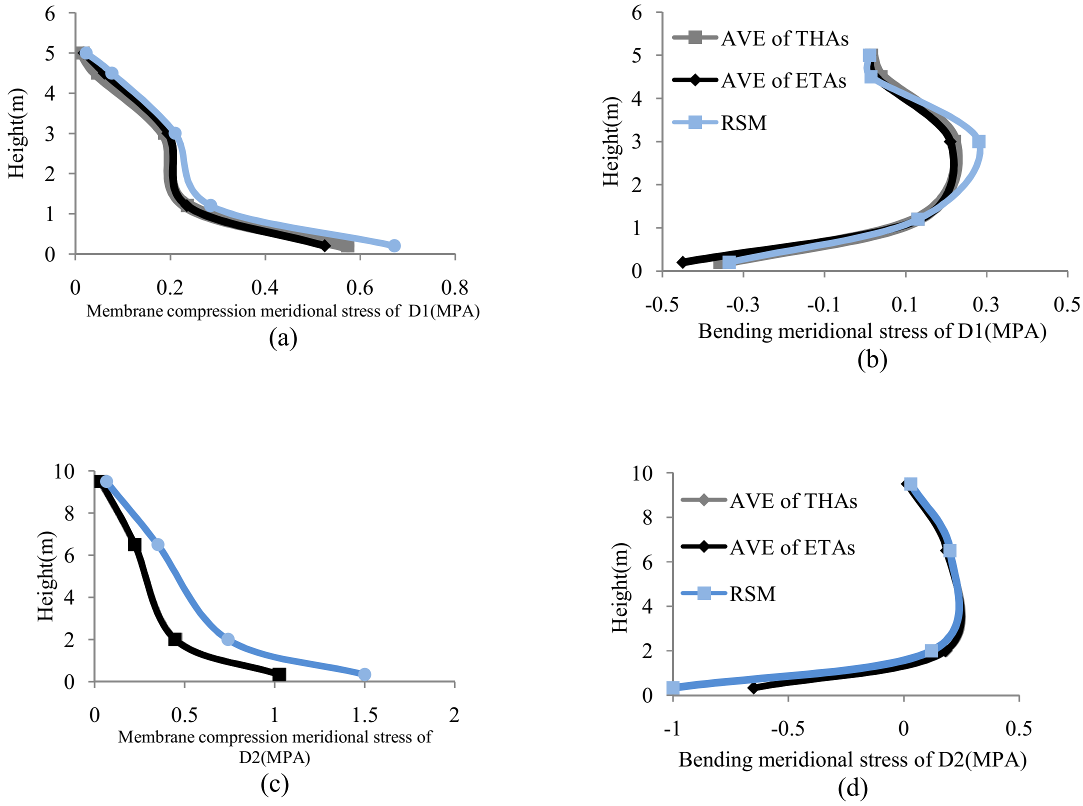
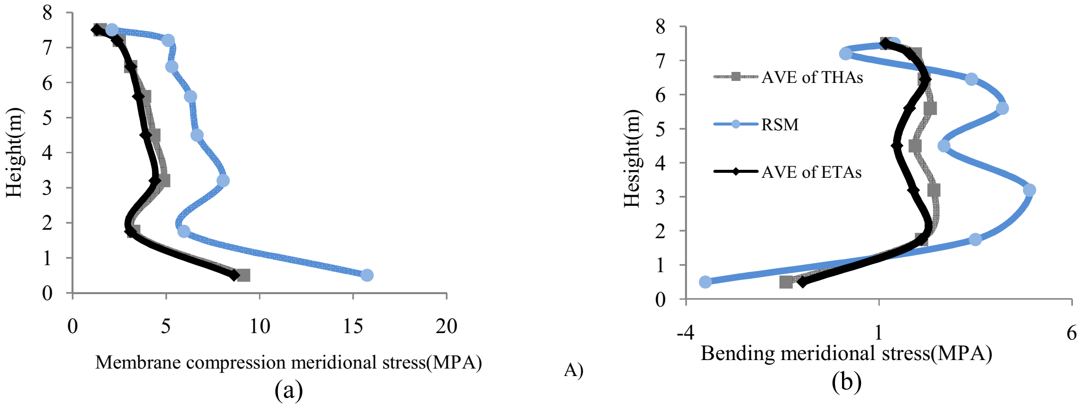


(a) (b) (c) (d)

**Fig. 12.** Meridional Stress distributions for 2 studied domes



(a) (b)

**Fig. 13.** Meridional Stress distributions for R1

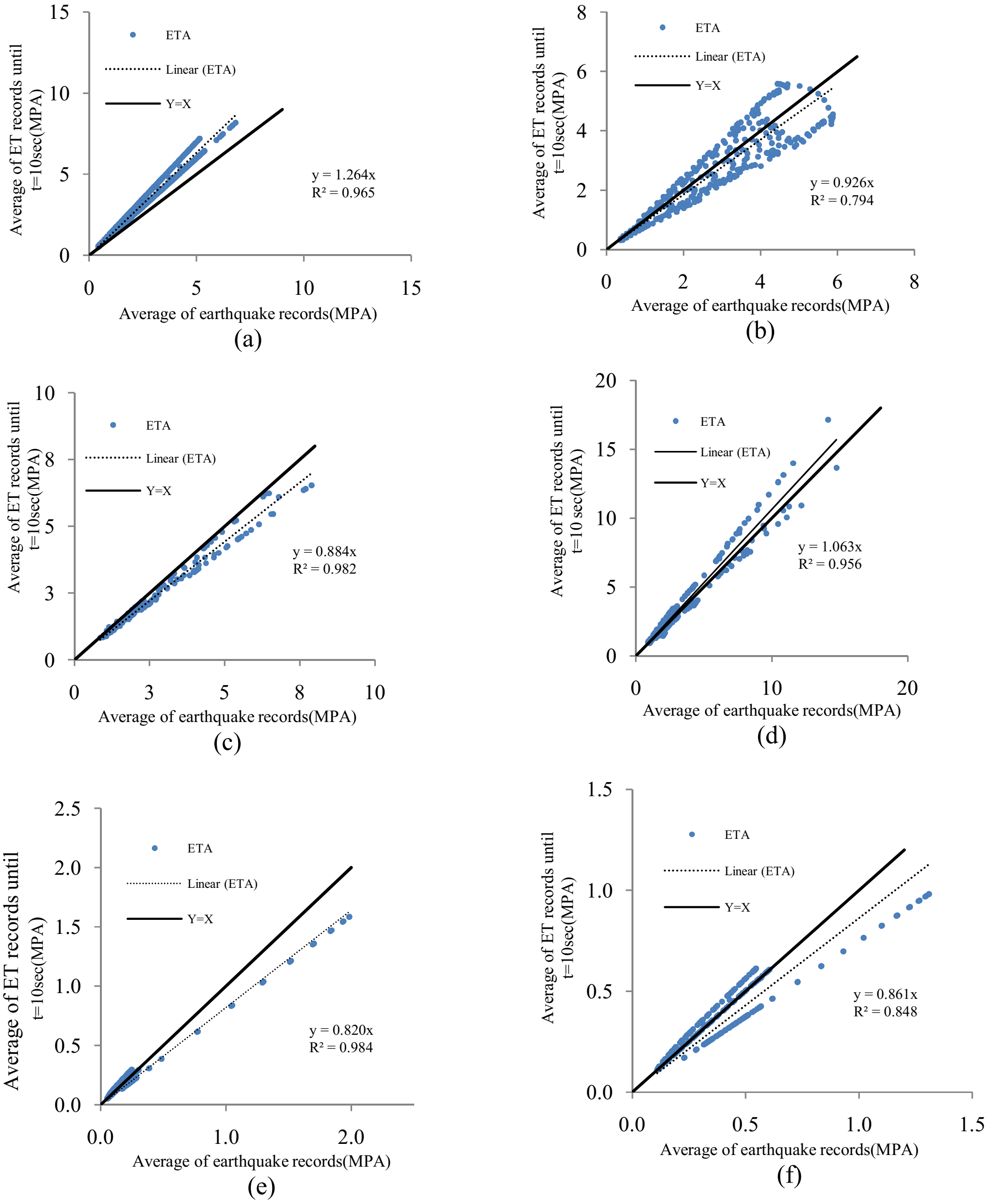


**Fig. 14.** Correlation diagram of Max. von-Mises stresses at various elements between THA and ETA with their trend lines, (a) C1, (b) C2, (c) R1, (d) R2, (e) D1, (f) D2

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## Nomenclature

| | |
|---|---|
| $a_g(t)$ | Ground acceleration |
| ET | Endurance Time |
| ETA | Endurance Time analysis |
| RSM | Response spectrum method |
| $S_a$ | Acceleration response |
| $S_a(T,t)$ | Acceleration response for period T at time t |
| $S_{aC}(T,t)$ | Codified design acceleration spectrum for period T |
| $S_{aT}(T,t)$ | Target acceleration response for period T at time t |
| $S_u(T,t)$ | Displacement response for period T at time t |
| $S_{uT}(T,t)$ | Target displacement response value for period T at time t |
| T | Free vibration period (s) |
| TH | Time History |
| THA | Time History analysis |
| $\alpha$ | Weighing factor in optimization target function |
| $\xi$ | Damping ratio |