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Seismic Analysis of Concrete Folded Plates

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Abstract

Concrete roof-folded plates have been shown to be inherently resilient to earthquakes, despite limited research on the reasons for their apparent seismic resistance. It is possible to make very thin, folded concrete plates because of their high structural efficiency. It is implicitly resistant to earthquake forces because thin, folded plat structures are relatively lightweight. Typically, folded plate structures are designed to perform under ideal gravity loads that are transported primarily as a result of membrane activity across the surface. It is possible for concrete-folded plate structures to be damaged by bending stresses when earthquakes induce unexpected horizontal forces. Through a parametric analysis of an 8-cm-thick concrete roof folded plate structure, it has been shown that thin concrete roof folded plates with a span < 30 m can be intrinsically earthquake-resistant. Despite having a low mass and high geometric stiffness, these buildings have fundamental frequencies that are substantially higher than those connected to seismic events that actually occur. This characteristic causes the folded plate to behave elastically under earthquake excitation without exceeding the maximum concrete strength. The vertical components of earthquake vibrations exert greater stress on a shallow, folded plate than the horizontal components. The values of the stresses imposed by the changing span were relatively small. They ranged from (3.5-4.4) MPa for the Landers earthquake, while for the El Centro earthquake, they ranged from (2.7-8.6) MPa. In addition, by raising the folded big plates and inclining them to a greater angle, it will become more common and lessen the harm caused by earthquake shaking in the vertical direction. In general, this paper aims to present an examination of earthquakes and their consequences for folded concrete plates.

Keywords: Folded plate, Earthquake, Shell concrete, Finite element method, ANSYS software.

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1. Introduction

The folded plate belongs to the class of stressed skin structures, which are characterized by a small flexural rigidity of the skin; Membrane forces act primarily in their planes to carry loads. Due to the wide variety of reinforced concrete folded plate structures used in modern construction, their behavior under seismic conditions is unclear. Since folded plates can be made in a wide variety of geometrical configurations, it is still believed that the available understanding is limited, making it necessary to develop recommendations that will be used in the study of folded plate structures subjected to seismic loads as general guidelines. It is therefore necessary to propose a methodology for learning the behavior of folded plate structures under seismic loads in order to meet certain objectives. To rationally design new structures and evaluate existing structures, it is imperative to estimate the response of buildings to strong ground motions. There have been several efforts by researchers to address such limitations by developing simplified analysis methods [1], [2]. It has become widely accepted that response spectrum analysis is a useful tool for evaluating and designing structures based on performance during seismic events. The most common method in structural engineering practice to estimate seismic demands is to use response spectrum analysis, which is generally used in structural engineering practice [3]. To determine whether it is accurate for large-span spatial structures, it must be studied in detail. This paper discusses the application of analysis to concrete folded plate structures. An ANSYS 21 R2 finite element [4] package is used to perform a complete analysis of folded plate structures using a three-dimensional finite element model. The folding and curvature of concrete plates is more stable against seismic loads, where it is necessary to investigate the behavior of the concrete plate to ensure the integrity of the structure and not to be subjected to cracks and collapse [5].

For many reasons, folded plates are very popular. Some of their advantages are similar to cylindrical long shells in that they can span large distances, due to their ease of formwork, they are cheaper than curved cylindrical shells, their aesthetic appearance and their small thickness make them more pleasing than shells (their thickness about 1/200 of the span). Joints are to be stiff and should not undergo any angle changes under the action of loads in order to remain rigid. A folded plate cannot be classified as a pure shell structure whose strength is derived from its curvature. The longitudinal bending of folded plates produces stresses similar to membrane stresses in shells, in addition to the transverse bending as a frame. In the longitudinal direction, these stresses are reinforced at the mid-depth of the plates [6].

In some cases, tensile reinforcement may not be required in folded plates. To resist temperature and shrinkage stresses, as well as local stresses caused, for example, by maintenance workers, a minimum amount of reinforcement is provided. As a minimum, BS 8110 recommends that concrete be reinforced with 0.13% of its gross cross-section [7]. According to ACI 318-19, these are quantified at 0.18% [8].

2. Structure description

2.1. Model of structure

Solid elements (SOLID65) with 8 nodes are used to model the concrete shell material, which includes three degrees of freedom at each point and translations in x, y, and z. In addition, this element is capable of plastic deformation, cracking in the x, y, and z directions, until it reaches the crushed concrete [9]. In the folded plates study, a concrete shell roof structure with a different size plan is analyzed parametrically to determine the impact of shell shape on seismic resistance and vibrational characteristics. This study assesses the performance of folded plates through response spectrum analysis of recorded spectrums. It determines the critical design parameters that will produce a shell structure that is more durable for the same plan area, as well as more resistant to deformations and stresses.

Three groups of folded plates were represented, where the first group dealt with the effect of changing the plan dimensions retaining an 8 cm thickness and a 45-degree slope for the plates. The second group dealt with the effect of changing the thickness with a constant plan area of 20 × 20 m and an angle of inclination of 45 degrees as well. As for the last group, the effect of the angle of inclination of the folded plates was demonstrated, with a fixed thickness of 8 cm, and a fixed plan area also of 20 × 20 m. All plates are supported by simple support and are bound on all sides except in the horizontal direction parallel to the edge, show in Fig. 1. Table 1 lists the material properties used in ANSYS 21R2 finite element modeling.

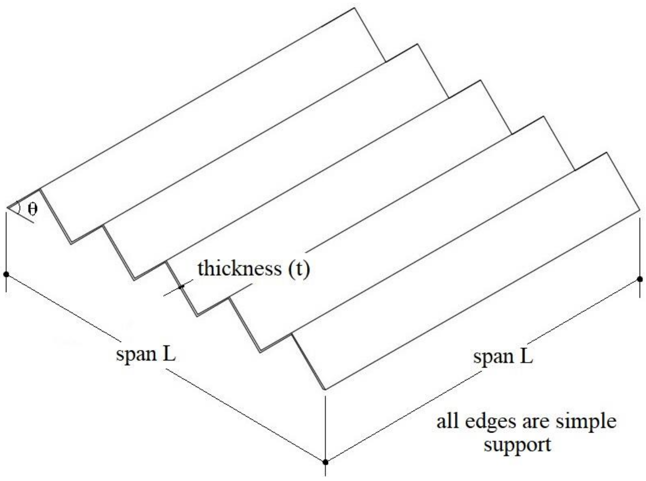

Fig. 1 Folded plate model.

Table 1. The properties of the materials used in the parametric study [10].

No.	Properties	Value	Unit
1	Compressive Strength	30	MPa
2	Tensile Strength	3	MPa
3	Youngs Modulus	21.5	GPa
4	Density	2400	kg/m^3
5	Poisson's Ratio	0.2	-

2.2. Seismic analysis

The seismic analysis describes how a structure reacts to earthquakes and is a subset of structural analysis. In regions prone to earthquakes, structural assessment and retrofitting are part of structural design and engineering.

When an earthquake occurs, shells are capable of wavering back and forth. Shell response is known as the "fundamental mode", and it is the lowest frequency. There is, however, a higher mode of response for most shells, which is activated only during earthquakes. Historically, earthquake resistance was regulated by designating a lateral force equal to a proportion of the building's weight. Originally, this approach was incorporated into the appendix of the Uniform Building Code of 1927, used mostly on the west coast of the United States. Later, it was discovered that the dynamic properties of the structure influenced earthquake loads. As early as the 1930s, a concept known as "response spectra" was developed, however, it was not until 1952 that a joint committee of the San Francisco Section of the American Society of Civil Engineers and the Structural Engineers Association of Northern California proposed determining lateral forces based on the building period (the inverse of frequency) [11].

2.3. Seismic effects and spectral analysis

Analyses are performed based on an entire spectrum of responses. In addition to the examination of the response spectrum, the fundamental frequencies of the folded concrete plates also provide an indirect indication of the reaction. Calculation of displacements and stresses involves calculating the maximum values. For the undamped free vibration response of the structure, the analysis involves calculating three-dimensional models and natural frequencies. Full subspace modal analysis is the method selected for the modal analysis. This method uses the square root of the sum of the squares to combine modalities for each principal direction. Fig. 2 shows the seismic spectrum of the Landers earthquake's vertical components in California, USA, 1992. This earthquake input was used in model calibration as the earthquake response of another shell reported in [5]. In addition, the earthquake's vertical component made it particularly relevant. When it comes to the folded plates this article studied. The importance of the vertical component outweighs that of the horizontal component. Another spectrum refers to the 1940 El Centro earthquake that occurred in Southern California. Figure 3 it is preferable to perform a response spectrum analysis over a time history analysis because it is more computationally efficient, making it possible to consider more parametric variations. Additionally, given that the shells in this study behave elastically, they only have a significant effect on the maximum response of the structure, whereas the evolution of the response over time offers little useful information.

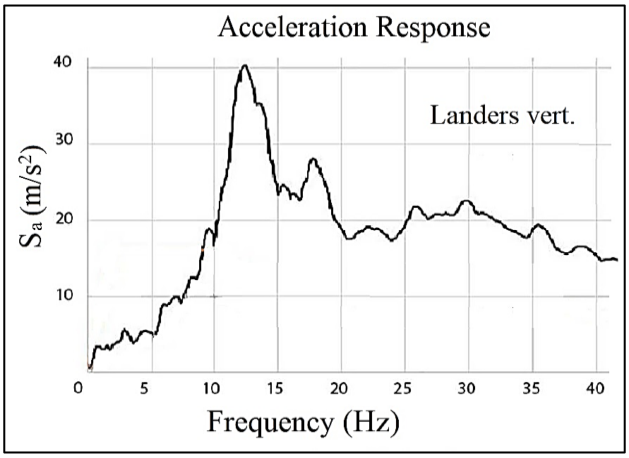

Fig. 2 Landers earthquake vertical acceleration response spectrum.

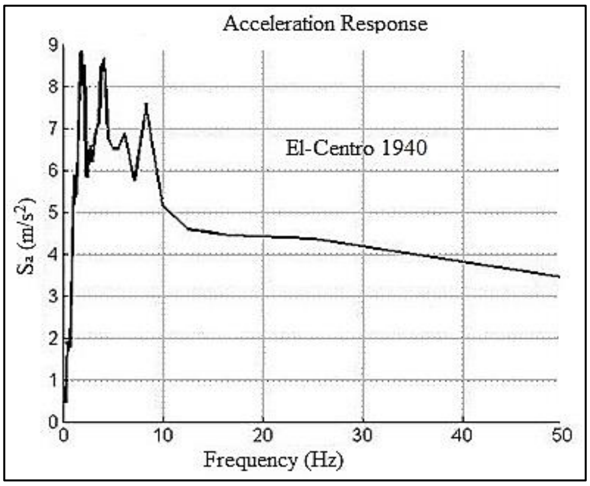

Fig. 3 El-Centro earthquake vertical acceleration response spectrum.

3. Results and discussion

3.1. Modal Analysis

Modal analysis in structural engineering determines a structure's natural resonance periods by using its overall mass and stiffness. There is a great deal of importance to noting these vibration periods in earthquake engineering since the natural frequency of folded concrete should not match the frequency of expected earthquakes in the region where the building will be constructed. In the event that the natural frequency of a structure matches the frequency of an earthquake, there may be structural damage as the system continues to resonate [12]. Shells such as folded plates that must keep natural frequencies away from previous earthquake frequencies in the same area also require modal analysis [13].

Generally, higher fundamental frequency folded plates can resist external forces that are horizontal and vertical. With rising frequency, there is usually a reduction in displacement response. According to the seismic spectrum, in spaces with a size of 50 to 60 meters, there is a modest variation in the low frequencies, which results in higher deformations (Fig. 4). With increasing concrete thickness (Fig. 5), the folded plates' frequency increases, resulting in reduced deformation. In Fig. 6, as the inclination angle increases, the rigidity of the folded plate structure increases, resulting in decreased deformations. For these results, the Landers and El Centro seismic studies were adopted.

The seismic behavior of folded plates can be understood by determining whether the fundamental frequencies of analyzed folded plates fall within these low-frequency ranges and by determining the parametric variations of initial plate shapes whose fundamental frequencies are at the highest. As long as the folded plate's fundamental frequencies increase, the plate structure will remain elastic. If an elastic limit is exceeded on reinforced concrete folded plates, plastic hinges form, reducing the plate's stiffness and thereby its fundamental frequency. Accordingly, thin reinforced folded concrete plates can be considered elastic under the adopted approach.

Under self-weight, the stress values are minimal throughout the folded plates. Figure 7 shows the stresses of the concrete folded plates with dimensions of 20 × 20 m, with an 8 cm thickness and a 45 degree inclination. At the top of the concrete shell, the highest stress values are located due to its self-weight. As long as the maximum permissible compressive and tensile stresses are never exceeded under self-weight, the concrete folded plates will not collapse under self-weight.

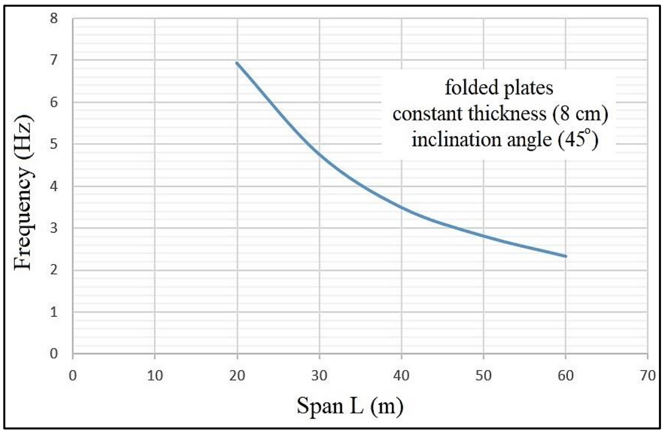

Fig. 4 Variation of frequency-span for reinforced concrete folded plates with a constant thickness of 8 cm.

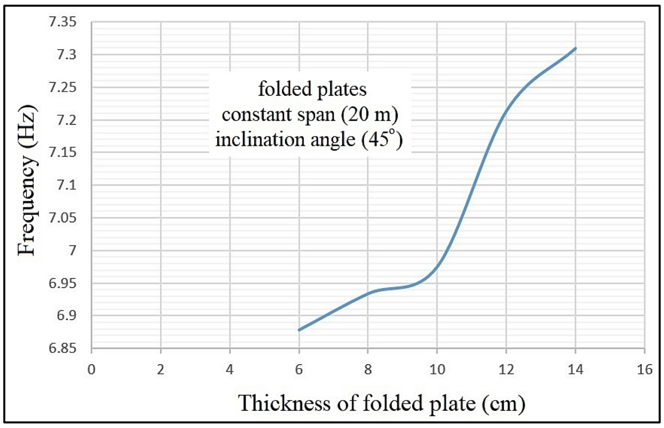

Fig. 5 Variation of frequency-thickness for reinforced concrete folded plates with a constant span 20 m.

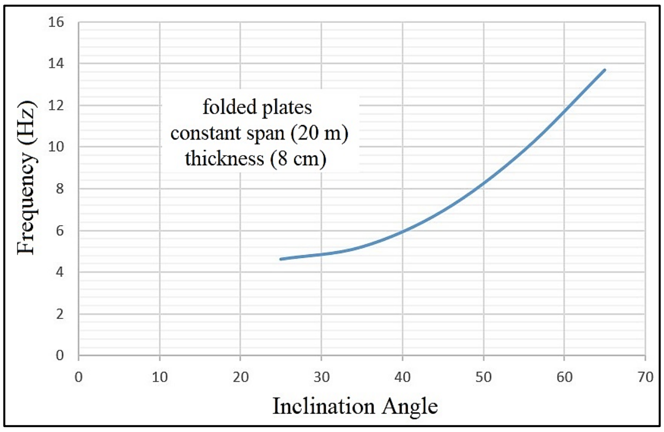

Fig. 6 Variation of frequency- inclination angle for reinforced concrete folded plates with a constant thickness of 8 cm.

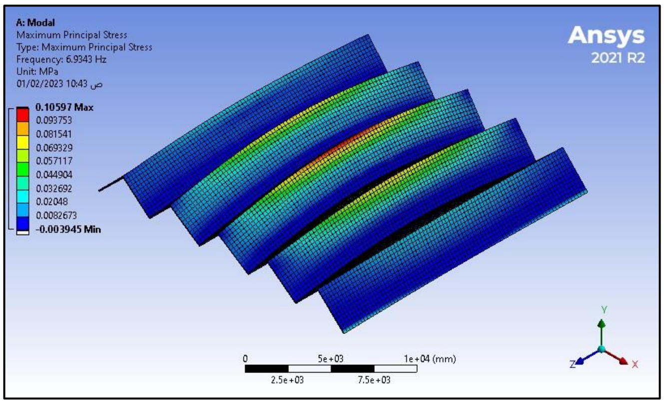

Fig. 7 Maximum stress under self-weight with span (20 × 20) m.

3.2. Seismic analysis

The structural analysis includes seismic analysis, which calculates how a structure will respond to earthquakes. Structural assessment and retrofit are integral parts of structural design, earthquake engineering, and structural assessment in earthquake-prone regions. When an earthquake occurs, the folded plates may 'wave' back and forth. Folded plates respond with the lowest frequency, called the (fundamental mode). However, most folded plates have higher modes of response, which are activated uniquely during earthquakes. Models are based on two earthquake spectra: one for Landers (Fig. 2) and one for the earthquake of El Centro 1940 (Fig. 3). Given that the vertical earthquake of Landers' reaction is bigger than the horizontal component, it is more significant. (Around four times at the peak of the response). Compared with the typical behavior of earthquakes, only in near-field occurrences do huge vertical earthquakes occur, and they are typically more damaging [14]. The spectrum of lower frequencies is more present in the El Centro earthquake than in the Landers earthquake. Based on a study of the response spectrum, the vertical components of the Landers and El Centro earthquakes generally do not cause concrete folding plates to exceed it often 3 cm in deformation. (See Table 2).

Table 2. Folded plates with maximum normal stresses and vertical deformations.

Span (m)	Max. deformation (cm)		Max. normal Stress (MPa)	
	Landers	El-Centro	Landers	El-Centro
20	0.708	0.502	3.908	2.712
30	0.928	1.194	3.502	4.420
40	1.518	2.534	4.012	6.630
50	1.966	3.427	4.465	7.480
60	2.351	4.807	4.326	8.665

Furthermore, maximum stresses are much higher in the vertical component. Due to the shallow depth of the folded plates under investigation, this conclusion is not surprising. Thus, vertical loading, generally performed out-of-plane, is more damaging than horizontal loading, which is performed in the plane. Folded plates were subjected to normal stresses between (3.5–4.4) MPa imposed by the Landers earthquake, and the normal stresses brought on by the El-Centro earthquake were between (2.7–8.6) MPa. Since the concrete tensile strength (3 MPa) is often not exceeded, El Centro earthquake stress levels are typically within the acceptable range to sustain elastic behavior. However, the maximum permitted tension strength of concrete was exceeded in the Landers earthquake. which can affect the folded plates in some ways. These stresses would cause cracking in the folded plate structure and activate the reinforcement, reducing stiffness and affecting fundamental frequencies. Furthermore, in the case of 20-meter spans, the maximum principal stresses would not exceed 3 MPa under vertical earthquake loading, thus ensuring elastic behavior (Figs. 8 and 9).

3.3. Effect of folded plate dimensions

It will be shown that by altering the shape of the folded plates, the fundamental frequencies and stiffness can be altered, and extreme stress can also be avoided due to vertical excitations.

To lessen the pressures and deformations brought on by earthquakes, the first strategy is to increase plate thickness while maintaining the same span in order to raise the basic folded plate frequency. (see Figs. 5, 10, and 11). Each folded plate is retained at a 45-degree angle of inclination. It is still important to maintain the same plan size (20 × 20 m), and all other design parameters are kept constant as well. Increasing the fundamental frequency of the folded plate and adjusting its angle of inclination (see Figs. 6, 12, and 13) also reduces earthquake response. Each folded plate is uniformly thick at 8 cm. High-folded plates have greater geometric stiffness and almost linearly increasing fundamental frequencies.

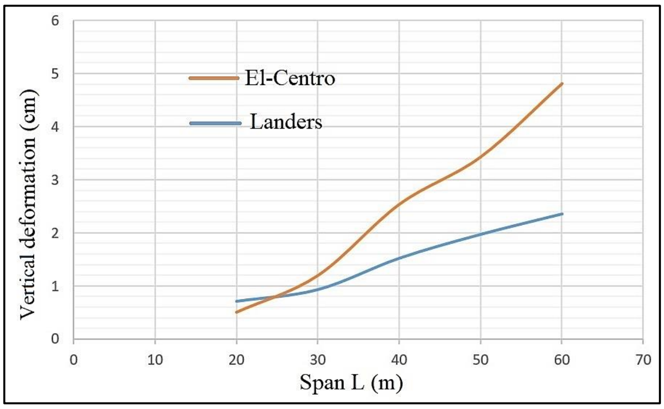

Fig. 8 Vertical deformation with a different span length of folded plates is caused by the vertical component of Landers & El-Centro earthquakes.

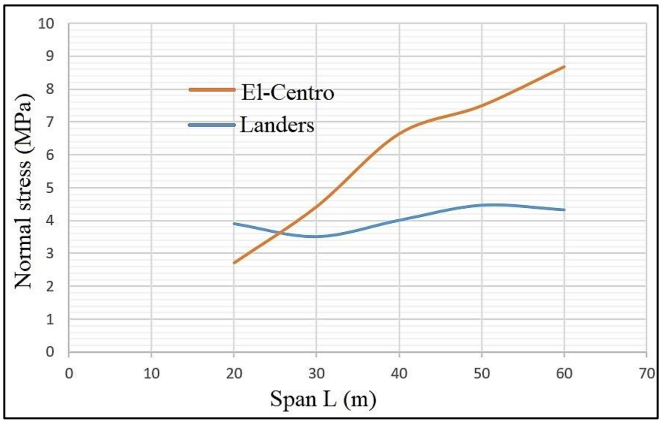

Fig. 9 Maximum normal stresses-span length of folded plates exposed to the vertical components of the Landers & El-Centro earthquakes.

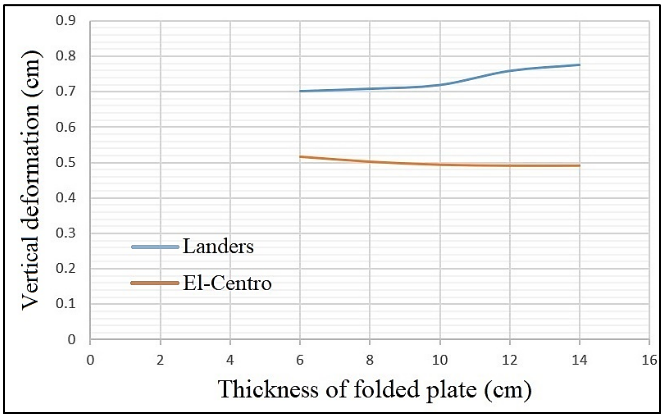

Fig. 10 Vertical deformation with a different thickness of folded plates due to the vertical component of Landers and El-Centro earthquakes.

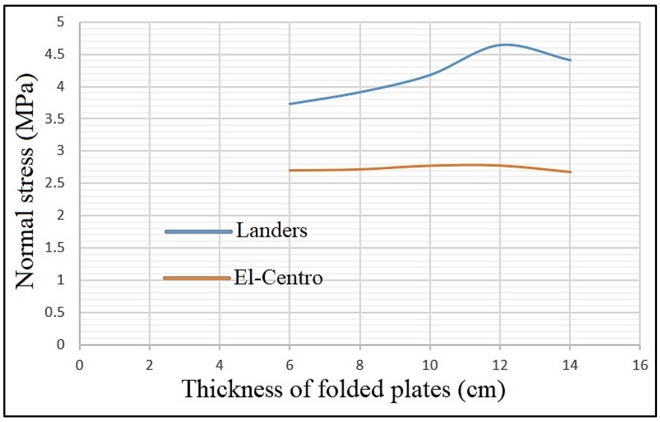

Fig. 11 The maximum normal stresses on folded plates with different thickness exposed to the vertical components of the Landers and El-Centro earthquakes.

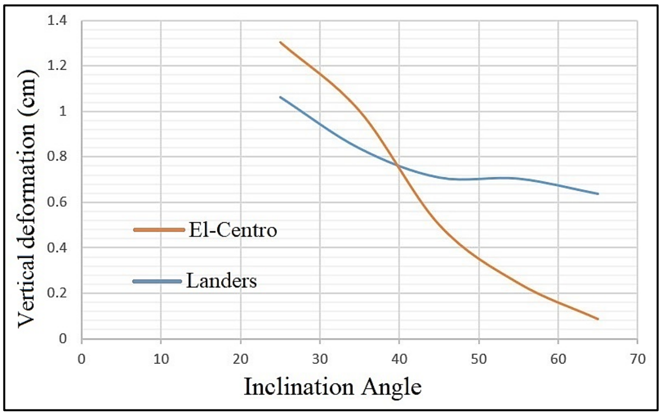

Fig. 12 Vertical deformation with a different inclination angle of folded plates due to the vertical component of Landers and El-Centro earthquakes.

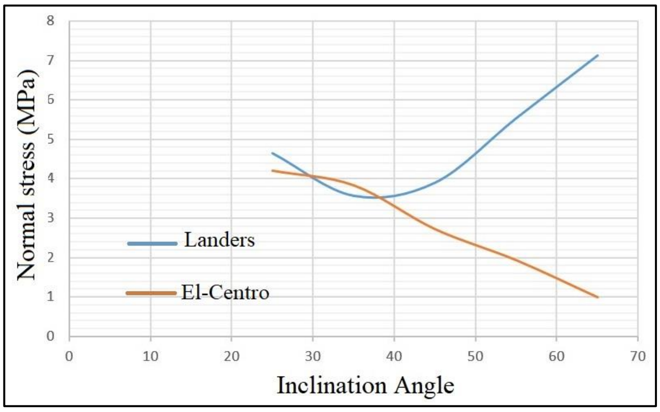

Fig. 13 The maximum normal stresses on folded plates with different inclination angles exposed to the vertical components of the Landers and El-Centro earthquakes.

4. Parametric analysis discussion

A response spectrum study demonstrates that, because of their continued elastic characteristic, folded plates containing high fundamental frequencies suffer lower damage to the structure from the examined earthquake stress. Considering how span affects the fundamental frequency, certain folded plates with a thickness of 8 cm have a reduced earthquake risk compared to others because their fundamental frequencies are higher. Since folded plates with shorter spans have higher fundamental frequencies, they display structural modes that are less sensitive to seismic activity than structures with similar forms but larger spans (Fig. 4). A folded plate with a span of up to 30 meters that is 8 cm thick will respond entirely elastically under both horizontal and vertical earthquake excitations. The fundamental frequencies of these structures are influenced by their stiffness and mass, as well as their high fundamental frequencies. Due to their lightweight construction and durability as a result of their folded geometry, these folded plates are not susceptible to damage during an earthquake.

The fundamental frequency of reinforced concrete folded plates decreases with increasing span; thus, earthquake damage is more likely to occur to them. With a span of 20 m and a thickness of 8 cm, reinforced concrete folded plates are relatively earthquake-resistant. There is a critical role for vertical components in most earthquakes, which makes this finding significant. However, these folded plates can be damaged by horizontal seismic components. It is interesting to note that the relatively shallow folded plates reported compared to horizontal, in-plane seismic stress are more sensitive to vertical earthquake stress in this work. Vertical earthquakes have the potential to produce stresses that are greater than the greatest tensile strength of concrete, leading to cracking and a loss in stiffness.

Under this vertical stimulation, to guarantee elastic behavior, the fundamental frequency of the folded plate can be raised. The best way to affect the fundamental frequencies is to alter the form of the folded plate. When vertical excitation is applied to folded plates, increasing the inclination angle reduces stress and deformation. Between 35 and 65 degrees of inclination angle, frequency increases almost linearly. As a result, it is best to increase the inclination angle and thickness of the folded plates in order to increase fundamental frequencies and reduce deformations. Changes in folded plate thickness have a less significant effect on fundamental frequency.

5. Conclusions

This study analyzes square-plan, folded roof plates made of reinforced concrete that are subjected to seismic loading. A study comparing and contrasting folded plates' fundamental frequencies is compared and contrasted with varied spans, deformations, and El Centro stresses, as well as an especially severe vertical seismic event at Landers. During the consideration of either horizontal or vertical ground motions, since their permitted compressive and tensile strengths have not been exceeded, folded plates (8 cm) thick and having concrete compressive strengths of 30 MPa behave elastically. The considered seismic actions are unlikely to damage folded plates with a span of 30 meters or more. These folded plates' high rigidity and lightweight make them demonstrate exceptional structural behavior. These characteristics result in only a slight effect on folded plate structural modes from earthquakes under study, most of which produce lower frequencies. Furthermore, these concrete folding plates' maximal tensile stress and span of 30 m can be outweighed by vertical seismic components, most frequently experienced during near-field earthquakes. These folded plates can have a greater fundamental frequency by increasing their rise and thickness, which reduces deformations and tensile stresses, thereby ensuring elastic response. Even though shape and span play an important role in the earthquake resistance of concrete roof folded plates, certain disastrous seismic events may not be able to resist earthquakes with proper shape. Structures can also be harmed by earthquakes with significant vertical components or by high-frequency seismic events that occur nearby. Other seismic security precautions should be taken into consideration in places where such earthquake occurrences are likely to occur. As stresses are transferred from folded plates to the earth's surface through a small quantity of supports, foundation isolation of the supporting could be a useful technique for seismic protection of folded plates.

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