Research Article

Buckling analysis of open-topped steel tanks under external pressure

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Abstract
Oil storage tanks are typically thin-walled structures which are susceptible to buckling under external load. This paper explores the buckling behavior of two in-services 100,000 m^3 open-topped tanks under external load by finite element simulation. The finite element analyses are first carried out to explore the stability of in-services tanks under the uniform external pressure and the wind load. And comparison with that three formulae which uses for calculating the critical buckling load of the tank under uniform external pressure. Then carried out the nonlinear buckling analysis by arc-length method, the results show that for in-services tanks, the linear elastic bifurcation analysis also is a good signal for the buckling load. Finally, this paper focus on the influence of wind girders and other reinforcement devices on the buckling behavior of in-services tanks and the strengthening mechanism of the stored liquid to in-service tanks with reinforcement devices. The reinforcement device affects the buckling behavior of the oil-storage tank by strengthening the stiffness of the top of the tank. However, the stored liquid through increasing the stiffness of the bottom of tanks to add the stability of tanks. And the result shows that compared to the oil-storage tank without reinforcement devices. The strengthening effect of the liquid on the tank containing reinforcement devices is more significant.

Keywords Buckling · Open-topped · Steel tank · LBA · Strengthening device · In-service

1 Introduction

In the twenty-first century, petroleum as an important strategic energy reserve has received great attention from various countries [1–3]. With the increase in oil production, the form of the storage tank has changed from the simple equal-wall tank to the large storage tank with variable wall thickness. Especially in recent decades, as the oil industry of numerous countries expands, the types of oil tanks have changed dramatically. Oil-tanks changes from tens of thousands of cubic meters to more than 100,000 m^3 of tanks.

Oil storage tanks are usually vertical cylindrical welded steel tanks, a typical thin-walled structure, which is prone to buckling and other damage under the action of wind load. Looking back on the past decades, the destruction

of oil storage tanks in typhoons has been innumerable [4–6]. Therefore, in order to avoid huge economic losses and environmental pollution caused by the destruction of oil storage tanks in typhoons. The buckling failure of oil storage tanks and similar thin-walled cylindrical structures under wind load has been extensively reviewed by scholars in various countries in the past decade [7].

Flores and Godoy [5] studied the buckling behavior of short cylindrical shells under strong wind loads by a numerical method, where the model adopts the tanks that were destroyed during the hurricane. Portela and Godoy [8, 9] discussed the buckling problem of tanks with conical or dome roofs caused by wind loads, tested the sensitivity of defects by geometric nonlinear analysis, and studied the influence of floating plate on the buckling behavior of tanks by using the same cylindrical model and wind load.

In recent years, with the development of finite element technology, Zhao et al. [10] through a large number of numerical analyses, illustrated the buckling behavior of the storage tank. Zhao and Lin [11] has compared the buckling behavior of tanks of different sizes and studied the similarities and differences of them under wind load. Maraveas et al. [12] made a comparison of current storage tank standards in Europe and API650, and propose some constructive comments about the current standards. Amir et al. [13] considered the effect of corrosion effect and aging of surface steel cylindrical storage tank under external pressure on its buckling behavior. Uematsu et al. [14, 15] based on finite element analysis, studied the wind resistance design problem of wind-resistant structure of open-topped storage tanks and the influence of top/medium anti-winds device on buckling behavior.

Most of these are based on the tank parameters in the design stage. It focuses on the influence of the imperfection or the reinforcement device on the buckling behavior of empty tanks under the wind load. However, in-service tanks almost have installed different size parameters of reinforcement devices. And before weather disasters such as typhoons or strong winds arrive, the storage state of the tank is often not simply empty or full. Therefore, depending on the numerical simulation method recommended by EN1993-1-6 [16], linear buckling analysis and geometrically nonlinear buckling analysis, this paper explored the buckling behavior of each storage tank under wind load. And study the strengthening mechanism of stored liquid to in-service storage tanks and the influence of reinforcement devices on the buckling behavior of storage tanks.

The main contents are as follows: Sect. 2 expatiates upon the structure prototypes of two tanks. The finite element models used for analyses and the wind pressures on both external and internal walls of tanks. Section 3 presents the linear buckling behavior of the storage tank under wind load. And compared the calculation accuracy of three formulae which use for calculating the critical buckling load of the tank under the uniform external pressure. Section 4 investigated geometrically nonlinear buckling behavior. Section 5 discusses the influence of reinforcement devices on the buckling behavior of tanks and the strengthening mechanism of the stored liquid to the in-service storage tank containing reinforcement devices. Finally, some valuable conclusions are drawn in Sect. 6.

2 Computational models

2.1 Structural prototypes

The tanks analyzed and compared in this paper are open-topped tanks of 100,000 m^3 in service of Sinopec, named

Tank1 and Tank2. Figure 1 shows the relative sizes of different tanks. The walls of those two tanks are similar in thickness and have reinforcement devices of nearly the same size. These two types of tanks reflect the structural parameters of a batch of open-topped tanks in China.

The two tanks have the same aspect ratio H/D = 0.27, radius-thickness ratio (calculated by minimum diameter thickness and maximum wall thickness) D/t = 2500 (Tank1), D/t = 2461 (Tank2). Table 1 listed specific wall dimensions. Table 2 listed the dimensions of stiffeners.

2.2 Finite element model

In this paper, the commercial finite element software Abaqus is employed to carry out this analysis. In Abaqus, the 8-node, quadrilateral, first-order interpolation, stress/displacement continuum shell element with reduced integration S8R5 chosen to discretize the cylindrical wall. The bottom boundary condition of the tank both fixed and the upper part is free. The material of cylindrical shell assumed to be isotropic elastic with an elastic modulus E of 2.06×10^5 N/mm^2 and a Poisson's ratio μ of 0.3. The finite element model of tanks is shown in Fig. 2.

2.3 External loads on tanks

The study of the external pressure of tanks can be divided into two parts: the uniform external pressure and the wind load. The form of uniform external pressure is simple, but the wind load distribution on the tank is various complicated.

The distribution of pressure around vertical cylindrical tanks under wind load has been studied in many literatures. Accordingly, the wind pressure P acting on the structure surfaces can be defined as [17]:
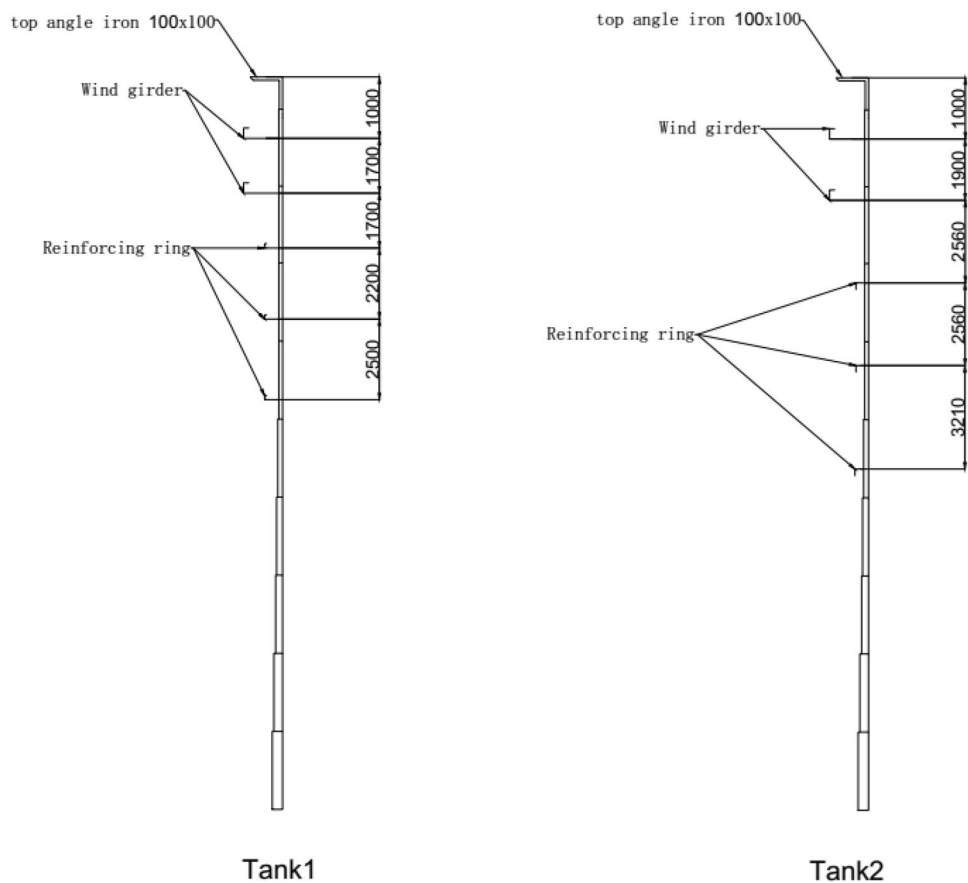
$$P = c_p q(z) \tag{1}$$

where c_p is the wind pressure coefficient and $q(z)$ is the velocity pressure of incoming wind which varies with the height.

Because the height of the tank is generally not high, so the change of wind load wind pressure coefficient in the height direction can be ignored. Those studies are only needed to consider the change of the circumferential upper-pressure coefficient of the tank. And in the study of the circumferential wind pressure coefficient of the tank more perfected, the distribution of wind loads can use the Fourier series decomposition expression as follows:

$$c_p(\theta) = \sum_{i=0}^{m} a_i \cos(i\theta) \tag{2}$$

Fig. 1 Section of *Tank1* and *Tank2* wall

where θ is the longitude measured from the windward, and a_i is the Fourier coefficient. Representative Fourier coefficients gained from typical studies and design codes are summarized in Table 3 [18–20].

It can be observed that although the Fourier coefficients matching to each wind pressure coefficient are different, their matching wind load distribution forms are generally the same (Fig. 3). The wind load has a symmetrical distribution of a stationary point, which shows positive pressure in the range of 0°–30° and negative pressure from 30° to 180°. The maximum positive pressure occurs at the stationary point and then decreases gradually. After converting to negative pressure around

Table 1 Tanks specific parameters

Course ($h_i \times t_i$)	Tank1 (mm)	Tank2 (mm)
1 (bottom)	2420×32	2420×32.5
2	2420×27	2420×24.5
3	2420×21.5	2420×21.5
4	2420×18.5	2420×18
5	2420×15	2420×15
6	2420×12	2420×12
7	2420×12	2420×12
8	2380×12	2380×12
9	2380×12	2380×12
10 (Angle)	100×10	100×10

Table 2 The dimensions of stiffeners

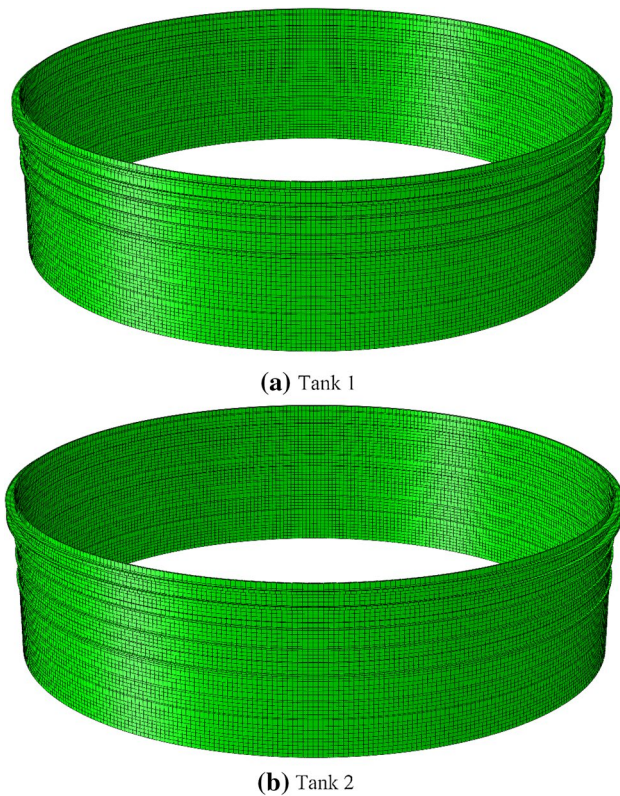|	Tank1		Tank2	
	Web size (mm)	Edge beam size (mm)	Web size (mm)	Edge beam size (mm)
1st Girder	1090×12	2×160×14	1150×12	360×96×9
2nd Girder	1090×12	2×160×14	1150×12	360×96×9
1st Ring	440×6	160×65×8.5	270×12	200×12
2nd Ring	440×6	160×65×8.5	270×12	200×12
3rd Ring	440×6	160×65×8.5	270×12	200×12

(a) Tank 1

(b) Tank 2

Fig. 2 Tanks finite element analysis model

30°, the maximum negative pressure is obtained about 80° and then becomes stable at 135°–180°.

It should be noted the coefficients only apply to the fixed top storage tank. For tanks with open-top, an extra uniform negative wind pressure coefficient must be subtracted to take account of the internal suction pressure [20]:

$$c_p = \begin{cases} -0.8 \ H/D \geq 2 \\ -0.5 \ H/D \leq 1 \end{cases} \qquad (3)$$

In this paper, the pressure distribution is from Rish [18]. Figure 4 has shown the circumferential distribution of wind pressure coefficient considering internal suction.

3 Linear buckling analysis

The linear buckling analysis is based on the linear elastic theory of small displacement and small strain. In other words, the equilibrium equation always established in the initial configuration of the structure at all stages of external force. When the load reaches a certain critical value, the configuration of the structure will suddenly jump to another subsequent equilibrium state, which is called buckling. It is called pre-buckling before the critical point and post-buckling after critical point [21, 22].

Linear buckling analysis that ignores geometric changes and material degradation will provide a preliminary assessment of buckling behavior, get a critical buckling load of the tank. In this paper, the buckling of the tank under wind load and uniform pressure has been analyzed.

3.1 Linear buckling analysis of storage tanks under uniform pressure

In the early study of tanks' stability, because of the lack of clear wind load distribution, the uniform external pressure was usually used instead of the wind load for roughly calculated the critical buckling load. Therefore, after making clear the distribution of the wind load on the tank, compare the buckling behavior of the tank under the wind load and the uniform external pressure is also significant.

3.1.1 Theoretical calculation of tanks under uniform pressure

For the calculation of critical pressure of tanks under uniform external pressure, storage tanks usually have calculated according to the standard regulations of the various countries on the construction states. One of the formulas calculate the critical pressure of the tank under uniform external pressure is according to the GB50341-2014 Standard [23]:

$$P_{UT1} = 16000 \frac{t_{min}^{2.5}}{D^{1.5}H} \qquad (4)$$

Second, according to the theory and numerical calculation method of Donnell, the critical buckling pressure of

Table 3 Fourier coefficients obtained from different sources

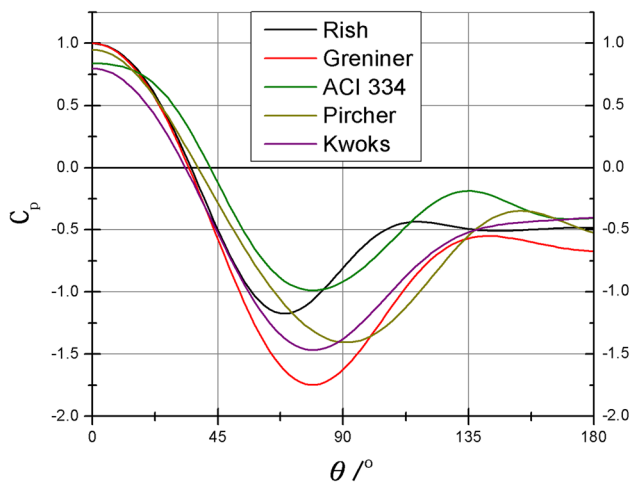|	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
Greiner and Derler [29]	−0.65	0.37	0.84	0.54	−0.03	−0.07		
Rish [18]	−0.387	0.388	0.533	0.471	0.166	−0.066	−0.055	
ACI334 [19]	−0.264	0.342	0.542	0.387	0.053	−0.077	−0.004	0.0341
Pircher et al. [20]	−0.5	0.4	0.8	0.3	−0.1	0.05		
Macdonald et al. [30]	−0.55	0.25	0.75	0.4	0	−0.05		

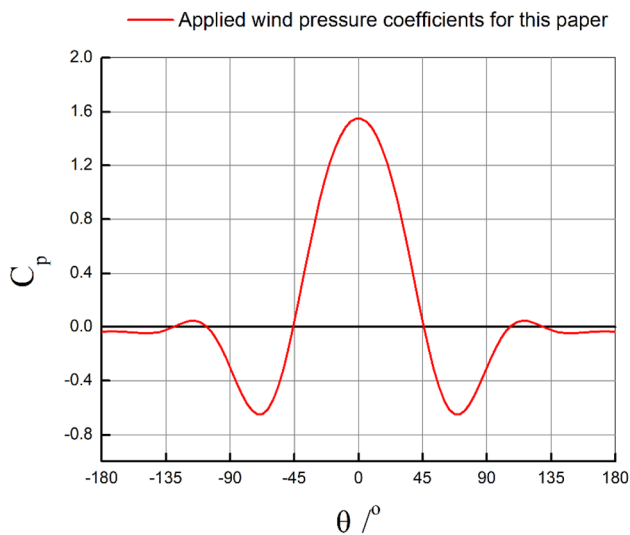**Fig. 3** Distribution forms of Wind load corresponding to different wind pressure coefficients

Fig. 4 Applied wind pressure coefficients for this paper

storage tank under uniform external pressure can be calculated by the following formula [24]:

$$P_{UT2} = \frac{2.59Et^2}{HD\sqrt{D/t}} \qquad (5)$$

Also, according to the calculation method of external pressure stability of short cylinders in GB150-2011, the critical pressure of storage tank under external uniform pressure can be calculated [25]:

$$P_{UT3} = \frac{2.6E(D/t)^{-2.5}}{(H/D) - 0.45(H/t)^{-0.5}} \qquad (6)$$

where E is the elastic modulus and t is the uniform thickness of the cylinder. For stepped shells, the equivalent height of the cylinder H and equivalent thickness t can be calculated by the following equations [24]:

$$H = \sum h_i \sqrt{\left(\frac{t_{min}}{t_i}\right)^5} \qquad (7)$$

$$t = t_{min} \qquad (8)$$

where h_i, t_i is the height and thickness of shell course, respectively, and t_{min} is the thickness of the thinnest shell course.

The critical uniform external pressure of buckling calculated by theory formulas for different tanks are summarized in Table 4.

3.1.2 Comparison of linear buckling analysis results and theoretical calculation results of storage tanks under uniform external pressure

The storage tank model of *Tank1, Tank2* without strengthening devices was established in the finite element software Abaqus. Figure 5 shows the buckling modes of tanks without strengthening devices under uniform pressure.

Table 5 listed the buckling loads P_{UL} obtained by the linear buckling analysis of the storage tank under the uniform external pressure and the error of the calculation results by theoretical formulas respectively. It can be seen that in the calculation of critical pressure of tanks, the GB50341 (P_{UT1}) method and the method based on Donnell (P_{UT2}) more conservative with an error of about 5% and 12%, the calculation method of GB150 (P_{UT3}) more radical with about 1% of the error.

Besides, Table 6 compares the results of critical pressure P'_{UL} calculation with the linear buckling analysis of tanks with reinforcement devices, listed the calculation and the error of calculation results by theoretical formulas.

In the course of calculating the tank with reinforcement devices, due to the equivalent height conversion of the unreinforced tank wall, there was a big error between the calculation result and the simulation result. The results showed the GB50341 (P'_{UT1}) method and the method

Table 4 Theoretical calculation of critical pressure for tanks without strengthening devices

P_{UT} (Pa)	Tank1	Tank2
P_{UT1} (Donnell)	929.78	914.37
P_{UT2} (GB50341)	864.93	855.91
P_{UT3} (GB150-2011)	970.00	955.9

Fig. 5 The buckling modes of tanks without strengthening devices under uniform external load
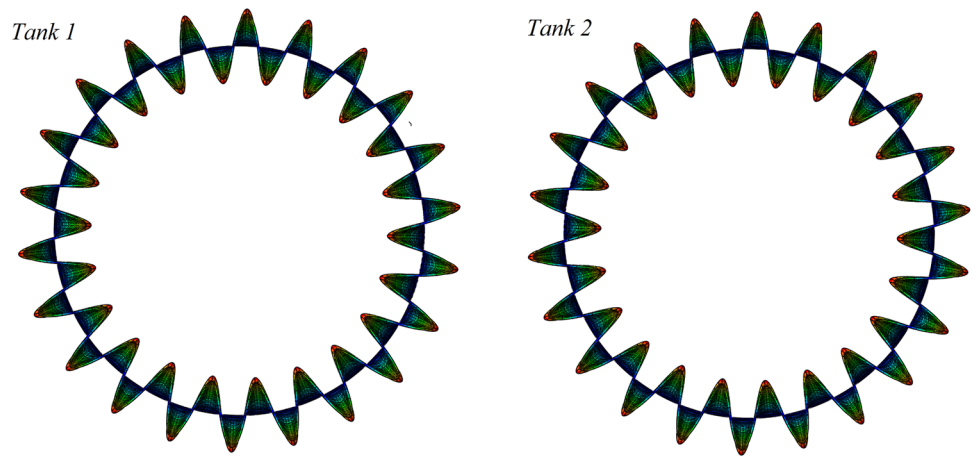
Tank 1   *Tank 2*

Table 5 Comparison of linear buckling analysis results and theoretical calculation results of storage tanks under uniform external pressure

	Tank1	*Tank2*
P_{UL} (Pa)	969.63	963.41
P_{UL}/P_{UT1}	1.04	1.05
P_{UL}/P_{UT2}	1.12	1.12
P_{UL}/P_{UT3}	0.99	1.01

Table 7 Comparison of linear buckling analysis results under uniform external pressure and under wind pressure

P (Pa)	*Tank1*	*Tank2*
P_{WL1}	666.11	675.72
P_{WL2}	666.11	675.72
P'_{WL1}	3297.6	5197.0
P'_{WL2}	3297.6	5197.0
$P'_{WL1,2}/P_{WL1,2}$	4.95	7.69

Table 6 Theoretical calculation of critical pressure for tanks with strengthening devices

P (Pa)	*Tank1*	*Tank2*
P'_{UL}	4987.7	7244.1
P'_{UT1} (Donnell)	3706.4	5821.2
P'_{UT2} (GB50341)	3469.4	5449.1
P'_{UT3} (GB150-2011)	4338.9	7494.2
P'_{UL}/P_{UT1}	1.34	1.24
P'_{UL}/P_{UT2}	1.43	1.32
P'_{UL}/P_{UT3}	1.15	0.96

based on Donnell (P'_{UT2}) more conservative, with a calculation error of 29% and 37%, the calculation method of GB150 (P'_{UT3}) more radical with about 9% of the error.

3.2 Linear buckling analysis of storage tanks under wind pressure

The first and second critical buckling load $P_{WL1,2}$ and $P'_{WL1,2}$ gained from linear buckling analyses for tanks under the wind load is listed in Table 7. It can be found in the first critical load equal to the second critical load for each tank. And the buckling load of the tank under wind load about 35% lower than that under uniform external pressure. The critical pressure of the two tanks under the wind load ($P_{WL1,2}$) is 666.11 Pa and 675.72 Pa. Figures 6 and 7 shows

the buckling modes of those two tanks under the wind load.

According to Table 7. It can be found, after the installation of reinforcement devices, the critical pressure of the tank greatly increased. *Tank1* increased by 495%, *Tank2* increased by 769%.

Obviously, *Tank2* gained a more strengthening effect than *Tank1*, about 274%. The increasing effect of the critical pressure of these two tanks is different because of the different installation positions of strengthening devices. The installation positions of reinforcing rings of *Tank2* more closing to the bottom of the tank.

4 Geometrically nonlinear analyses

The geometrically nonlinear buckling analysis needs to test repeatedly to gain accurate critical loads, and its calculation accuracy is related to the size of the applied load. And the accuracy of results can only be guaranteed if the applied load is slightly greater than the critical load. Therefore, the nonlinear buckling analysis of the storage tank has carried out in this paper to track the whole process of tank buckling.

This section has considered the geometrically nonlinear buckling behavior of the tank. And in order to gain the result of geometric nonlinear buckling analysis, all geometric nonlinear buckling analyses in this paper use very

Fig. 6 Vertical buckling modes for different tanks under the wind load (first modes)

(a) *Without reinforcement devices*   **(b)** *With reinforcement devices*
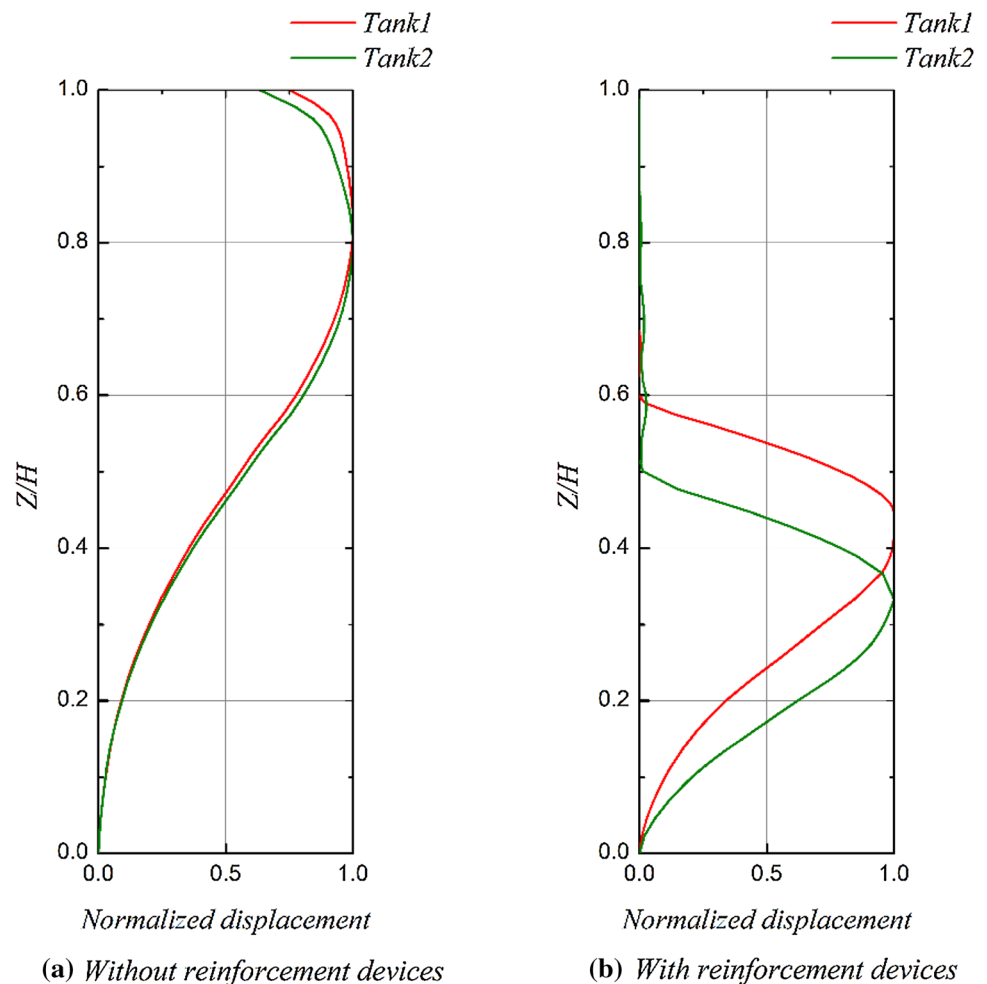
small same classical buckling mode imperfections as initial imperfections to facilitate the convergence of the calculation (the amplitude of the imperfections used is 0.01 times the thinnest wall thickness of the tank). Figure 8 plotted the load–displacement curves of tanks, in which the symbol Δ means radical displacement with inward positive. It can be found the buckling behavior of storage tanks is typically branch instability. And in the pre-buckling stage, the load–displacement curve is close to linear.

As shown in Table 8, the critical buckling load of geometrically nonlinear analysis (P_{WG} and P'_{WG}) under wind load is close to the result of linear buckling analysis ($P_{WL1,2}$ and $P'_{WL1,2}$). Figure 9 is the buckling deformation of the tank under the critical buckling load gained from the geometrically nonlinear buckling analysis. It can be found that these deformations are similar to the first-order waveforms of the eigenvalue analysis results of linear buckling analysis.

Through comparing the results of geometrically nonlinear analysis and linear buckling analysis. It can be believed the linear elastic bifurcation analysis is a good signal for the buckling load and rough deformation at the maximum

load point although it cannot predict the deformation exactly.

5 Influence of various factors on the stability of storage tanks under external pressure

In fact, for in-service tanks, there are many factors influenced the stability of tanks under external pressure. Such as the influence of the installation of strengthening devices, the influence of liquid stored in the tank and the common action of these two is discussed in this paper.

5.1 Influence of Tank's strengthening device

For the in-service tank, wind girders and reinforcement rings are generally arranged as reinforcement devices to keep their roundness when they are affected by wind load [26]. Although the size parameters and the installation position of reinforcement devices will be designed by using the national standards at the design stage. In fact,
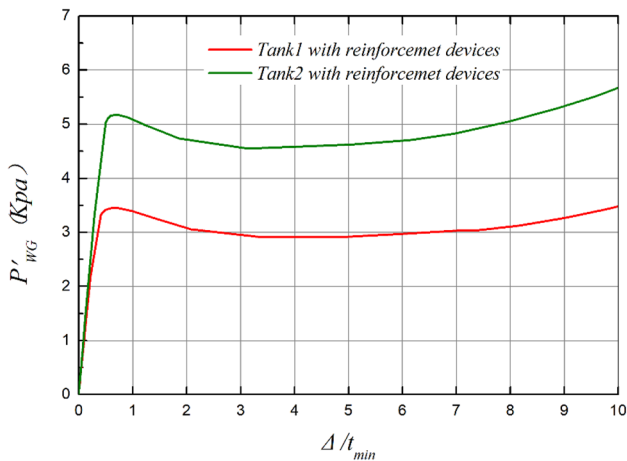
Fig. 7 Circumferential buckling first and second modes for different tanks without installed reinforcement devices under the wind load
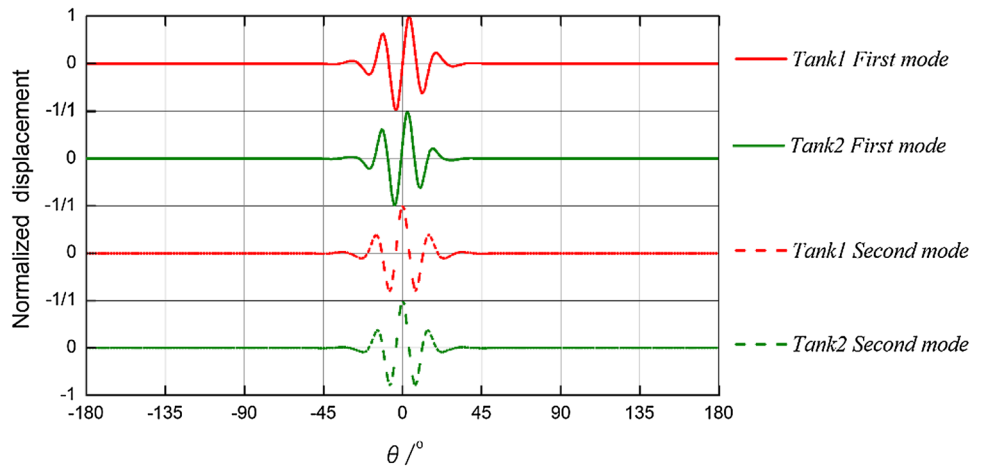
(a) *Without reinforcement devices*
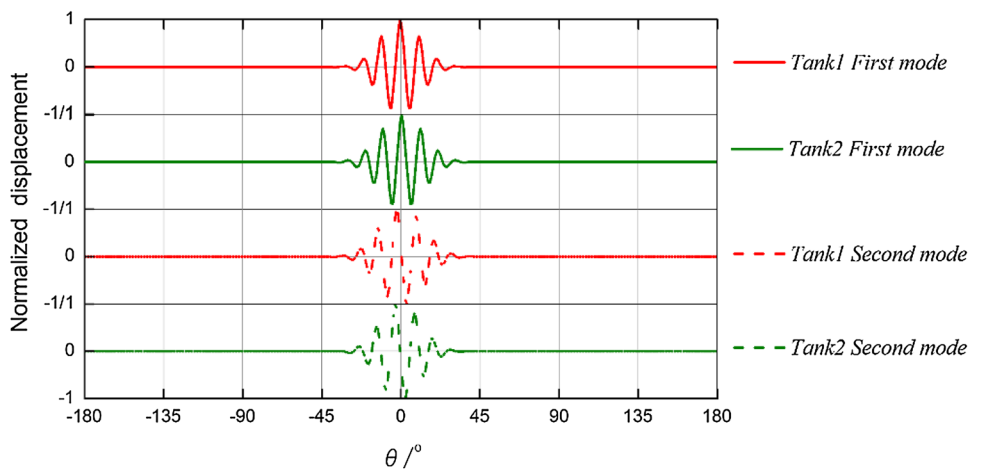
(b) *With reinforcement devices*

Fig. 8 Geometrically nonlinear equilibrium paths of tanks under the wind load

Table 8 Comparison of geometric nonlinear analysis results with linear buckling analysis results

P (Pa)	Tank1	Tank2
P_{WG}	627.71	641.54
P'_{WG}	3445.49	5177.57
P'_{WG}/P_{WG}	5.490	8.071
$P_{WG}/P_{WL1,2}$	0.942	0.949
$P'_{WG}/P'_{WL1,2}$	1.045	0.996

the installation position of the wind girder of the two in-service tanks always different. In this article, the installation position of reinforcement devices for two tanks shown in the following Table 9.

Review Fig. 6 and Table 8. It is obvious that the strengthening effect of *Tank2* slightly better than that of *Tank1*. The reasons may because the installation position of strengthening devices of *Tank2* is more dispersed and the position of the last reinforcement ring is closer to the bottom tank wall. Figure 6 shows that the deformation of the

Fig. 9 The buckling deformation of tanks gained from the geometrically nonlinear buckling analysis
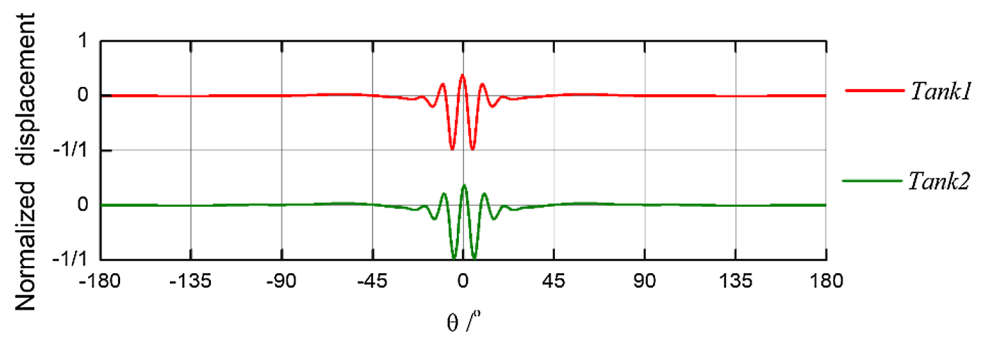
Table 9 Height of installation position of strengthening devices such as wind girders of two storage tanks (distance from tank bottom)

| Mounting height (m)	Tank1 (m)	Tank2 (m)
1st Girder	20.8	20.8
2nd Girder	19.1	18.9
1st Ring	17.4	16.34
2nd Girder	15.2	13.78
3rd ring	12.7	10.57

shell above the wind girder is reduced considerably, and for *Tank1* and *Tank2*, the displacement of the shell above the height of reinforcing rings installed is almost zero. And the location of the maximum buckling deformation of tanks with the installation of reinforcement devices obviously moved down. This means the reinforcement device significantly strengthens the stiffness of the upper part of the shell and improves the anti-wind buckling capacity of the shell.

5.2 Influence of stored liquid

The liquid stored in the tank produces two effects: (1) the internal suction caused by the wind disappears under the liquid level, (2) the static water pressure will be applied to the inner wall of the tank to offset the windward positive pressure [27, 28]. So the storage of liquid can improve the stability of storage tanks under wind load.

In order to understand the influence mode of liquid stored in the tank, several different liquid levels were used for analysis. The density of stored liquid reference engineering actual storage of liquid density (840 kg/m^3). And for tracking the change between buckling loads and the hydrostatic pressure more accurately, the loading sub-step of the hydrostatic pressure is 10% of the full-load stage.

Figure 10 shows the vertical buckling modes of the maximum displacement at different liquid levels in each tank. It can be seen that the effect of the stored liquid on the different tanks is similar. And with the increase of liquid
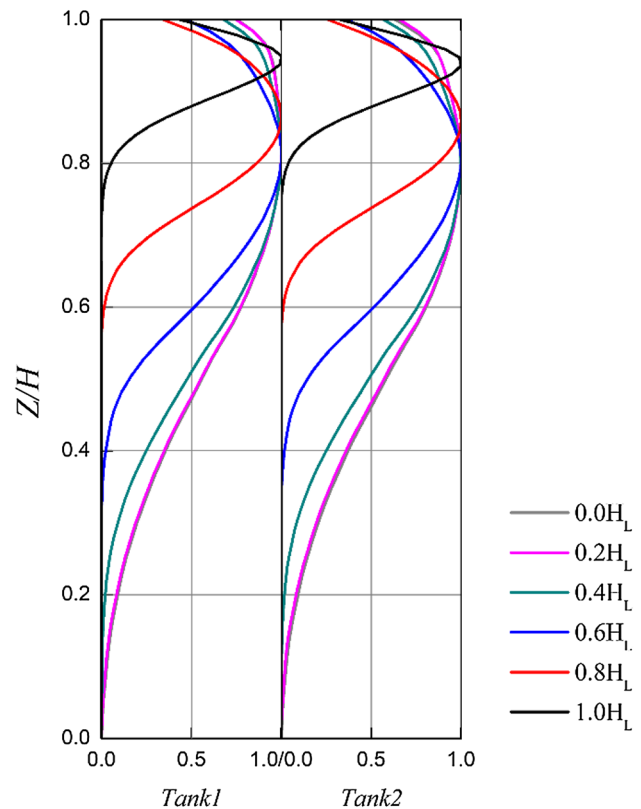
Fig. 10 The vertical buckling modes of tanks at different liquid level

level, the bottom buckling deformation of the tank is significantly reduced and the maximum displacement is constantly moving up. This is the opposite of the effect of reinforcement devices on the buckling behavior of the tank, which indicated the stored liquid significantly enhances the tank by strengthening the stiffness of the bottom of the tank, thus improving the stability of the shell under strong wind load.

And the normalized buckling loads with various liquid levels are summarized in Fig. 11. Due to the linear buckling analysis and geometrically nonlinear buckling results are near, only the linear buckling analysis results are given for discussion.
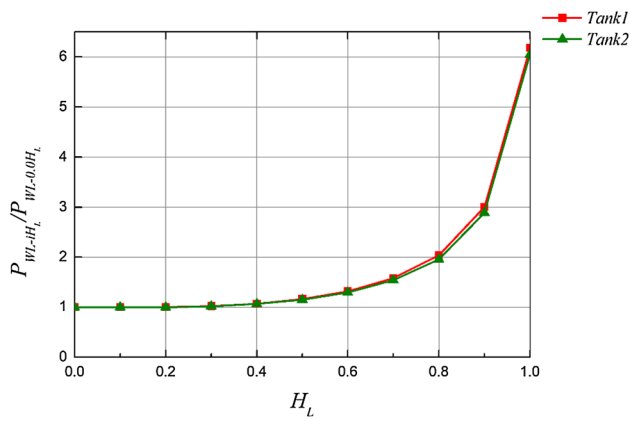
Fig. 11 Liquid level-load variation curve based on empty state

According to the results of analyses. It can be found that for the lower water level, $0.1H_L \sim 0.4H_L$, almost not improve the anti-buckling ability of those two tanks. After the middle water level $(0.6H_L)$, the wind buckling load of tanks generally begins increasing, and when the liquid level is close to a full tank, the wind buckling load of tanks increases greatly. It proves that it is effective to impound sufficient water for empty tanks before a hurricane to prevent tanks from buckling due to strong wind load.

5.3 Composite effect of the strengthening device installation position and liquid level on external pressure stability of storage tank

In fact, for in-service tanks, the strengthening of the tank is on reinforcement devices and stored liquid common effect. Figure 12 shows the vertical buckling mode of *Tank1* and *Tank2* (with reinforcement devices) under different liquid levels. For *Tank2*, it can be seen that with the increase of the liquid level, the maximum displacement of the tank is increasing. And there is a significant change in the buckling mode when the fluid level arrives the installation position of the reinforcement device (at $0.6H_L$ and $0.8H_L$). Figure 13 summarizes the normalized variation of the buckling load for linear buckling analysis of tanks with stiffeners based on empty states as the liquid level increases.

Besides, Fig. 14 shows the nonlinear equilibrium path under several liquid levels of *Tank1* and *Tank2* containing reinforcement devices based on the analysis results of empty tanks. According to the results of the linear buckling analysis and the geometrically nonlinear buckling analysis of the tank with the change of liquid level under the action of wind load. It can be seen that as follows:

(1) The existence of the strengthening devices has greatly improved the external pressure stability of
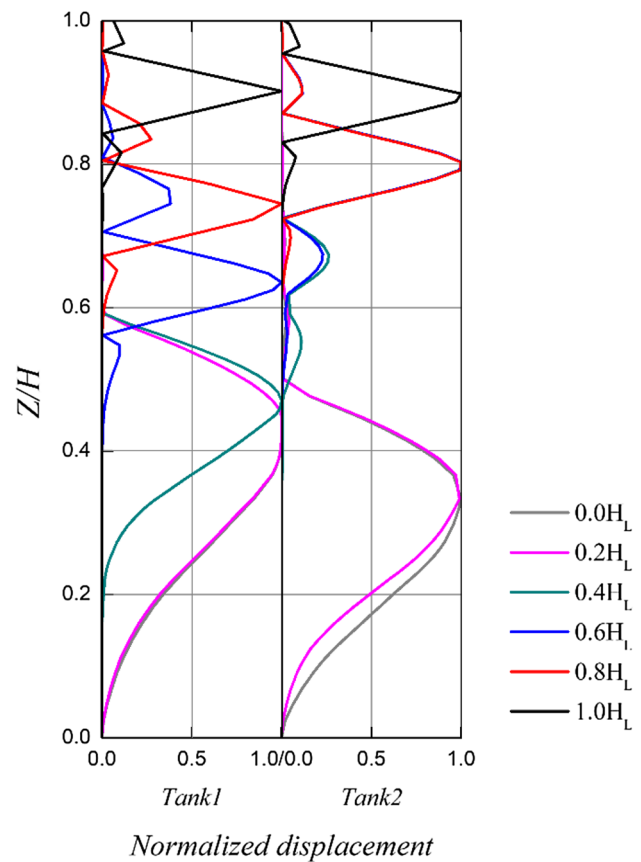

Fig. 12 The vertical buckling mode of tanks (with reinforcement devices) under different liquid levels

tanks. For *Tank1* and *Tank2* without strengthening devices, if they want to achieve the same enhance effect need to loading at least 90% of the stored liquid of those tanks.

(2) The enhancement mechanism of the strengthening device and the stored liquid on the stability of the storage tank under external loads are different. And make the effect of the liquid stored in the tank containing the strengthening device on the external pressure stability of the tank is partially offset, especially for *Tank2*.

(3) The weakening degree of the effect of different installation positions on the stability of the tank under external pressure caused by the stored liquid is different. If manufacturers want to enhance the stability of the tank under external pressure contained strengthening devices by storing liquid. It is necessary to analyze the installation position of the strengthening device for the specific storage tank.
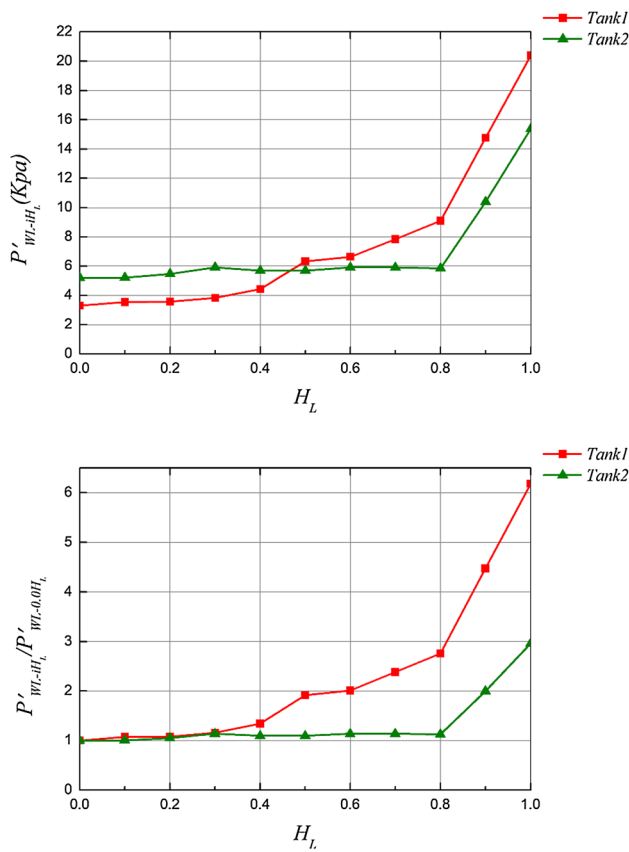
Fig. 13 Liquid level-load curve for tanks with reinforcement devices

Fig. 14 Nonlinear equilibrium path of *Tank1* and *Tank2* (with reinforcement devices) at several liquid levels

6 Conclusion

In this paper, a large number of numerical simulations have been conducted to study the effects of various factors on the stability of those two in-service tanks. The main conclusions of this paper can be summarized as follows:

(1) Among the comparison of formulas for calculating critical buckling pressure of storage tanks under uniform pressure. The theoretical calculation method based on Donnell is closer than the GB50341 method to the results of finite element analysis, and the results are slightly conservative. And the formula for calculating the critical pressure of the short cylinder in GB150 is also applicable to the equivalent tank model, which only has a small error compared with the finite element results.

(2) The stability of tanks under external pressure will be greatly affected by the different installation positions of the tank strengthening device. Taking those two in-service tanks studied in this paper as an example, the critical buckling load difference between those two tanks under the condition of no liquid stored is nearly 40%.
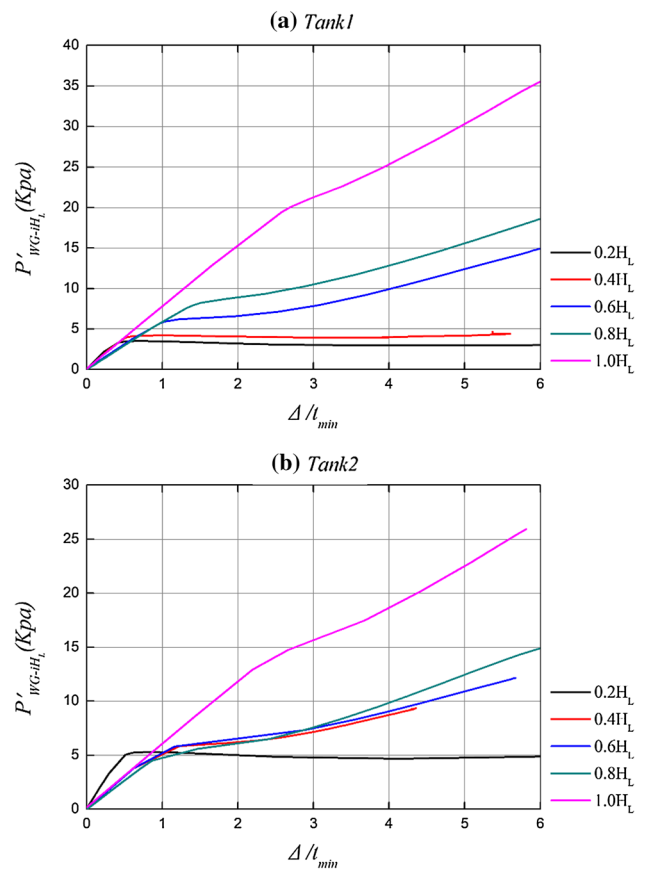
(3) When under the wind load, the effect of the stored liquid to the stability of similar tanks is consistent.

(4) The stored liquid enhances the anti-buckling ability of in-services tanks under wind loads by enhancing the rigidity of the bottom of the tank. While the reinforcement device enhances the ability by strengthening the rigidity of the top of the tank.

(5) The installation of the reinforcement device can effectively improve the wind buckling ability of the storage tank. And for in-services tanks which containing reinforcement devices, the stored liquid also can make positively interact with the reinforcement device to affect the stability under external loads.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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