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Effects of stiffness and configuration of brace-viscous damper systems on the response mitigation of offshore jacket platforms

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Abstract

We investigate the effects of a brace-viscous damper system on the dynamic response of offshore platforms. To do this, offshore jacket platforms with various distributions and three different configurations of brace-viscous damper systems - toggle, chevron, and diagonal configurations - and a wide range of brace stiffness are numerically modelled under the loading of irregular waves in ANSYS software. The dynamic response of the developed numerical model and its various brace-viscous damper configurations are validated against literature experimental and numerical results. Such a validation revealed an excellent agreement between the numerical results and the benchmark data. The results suggest that the standard deviation of the platform displacement given by a toggle configuration is less than that due to the chevron and diagonal configurations. Moreover, the maximum reduction of the base shear force is achieved by the application of the toggle configuration. Regarding the brace stiffness (area), for a reference damping coefficient of 500 N.m/s, a 54% increase in the brace area (from 42 to 91.8 mm²) results in a 21.26%, 38.61%, and 17.57% reduction in the structure displacement response for the diagonal, chevron, and toggle configurations, respectively. Using the results of the numerical simulations, we propose the spatially-optimized distribution of the brace-viscous damper system. Comparing the numerical results of this paper with those of field observations it was shown that the viscous damper with toggle configuration outperforms both the viscoelastic damper and uncontrolled platforms in terms of dynamic response.

Keywords: dynamic response of offshore jacket platform; brace-viscous damper system; toggle configuration; chevron configuration; diagonal configuration

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Nomenclature

$F_D(t)$	Force generated by the viscous damper (N)
C_D	Damping coefficient (Ns/m)
N	Constant parameter
$U(t)$	Viscous damper relative displacement along its axis (m)
$\dot{U}(t)$	Axial velocity of the viscous damper (m/s)
$sgn(\)$	Sign function
A_0	Amplitude of the viscous damper displacement (m)
t	Time (sec or s)
T	The period of viscous damper piston displacement (s)
m_f	Magnification factor
$F_h(t)$	Horizontal component of the force exerted by the viscous damper (N)
θ	Inclination angle of the damper ($Degree$)
$F_{ext}(t)$	External excitation force (N)
C_{Db}	Damping coefficient of brace-viscous damper system (Ns/m)
K	Structure stiffness (N/m)
K_b	Brace stiffness (N/m)
K'_{vb}	Energy distribution capacity of a brace-viscous damper system
$X(t)$	Structure displacement (m)
$\dot{X}(t)$	First time derivative of structure displacement (velocity; m/s)
$\ddot{X}(t)$	Second time derivative of structure displacement (acceleration; m/s^2)
H	Inter-story height (m)
D	Frame bay length (m)
θ_1	Horizontal angle of the lower brace ($Degree$)
θ_2	Vertical angle of the upper brace ($Degree$)
θ_3	Vertical angle of the damper ($Degree$)
L_1	Length of the lower toggle brace (m)
L_2	Length of the upper toggle brace (m)
m	Mass of the structure (kg)
$S(f)$	Spectral energy density (m^2/Hz)
f	Frequency (Hz)
γ	Peak enhancement factor (JOWNSWAP spectrum)
f_0	Peak frequency (Hz)
H_s	Significant wave height (m)
σ	Width parameter in JOWNSWAP spectrum
σ_{sd}	Standard deviation (m)
X_i	i^{th} platform displacement in x-direction (m)
$\bar{X}$	Mean of the platform displacements in x-direction (m)
M	Number of displacements
C_M	Added mass coefficient
C_I	Inertia coefficient
C_B	Buoyancy force coefficient
C_D	Drag force coefficient

1. Introduction

The operation of the oil and gas industry largely relies on offshore platforms. These, working in the offshore environment, are subjected to severe environmental loadings, such as wind, earthquake, and wave loadings, which causing strong vibrations of the offshore platforms [1,2]. The energy that transfers from the aforementioned dynamic loads to the offshore structures causes various modes of vibrations, which can threaten the structure functionality. The vibration continues until the transferred energy is completely dissipated. In the absence of energy dissipation systems (EDS), the dissipation of such transferred energy within the elastic range is very low, most being dissipated by friction in joints and micro-cracks in concrete structures. A direct way to mitigate the vibration of offshore platforms is to increase the stiffness of the platforms. The latter solution needs extra construction material and thus increases the costs [3]. As a result, in recent years, structural controlling technologies or energy dissipation systems have reached considerable success in the reduction of structure vibration [3–7].

Generally, energy dissipation systems are classified into various types such as active [8], semi-active [9], hybrid control [10], and passive energy dissipation system [11,12]. The main difference between such energy dissipation systems relies on the force delivery devices integrated with real-time processing evaluators and sensors within the structure. The optimal design of offshore jacket platforms can be achieved by exploiting the proper energy dissipation systems that mitigate the dynamic response of these structures.

Many studies have investigated the role of energy dissipation systems for the dynamic response mitigation of offshore structures [13–16]. Paul et al. [17] investigated the semi-active control of offshore jacket platforms under the action of various wave loads using the semi-active hydraulic damper (SHD). Their results suggested that an acceleration response control can be mainly achieved by semi-active control using SHDs. Lee et al. [18] studied the wave-induced vibrations of floating platforms equipped with tuned liquid column damper (TLCD) devices. Analytical and experimental results suggest that an accurately tuned TLCD system could effectively decrease the vibration amplitude and the resonant frequency of offshore platforms. Patil and Jangid [19] investigated the effects of viscoelastic, viscous and friction dampers application on the passive control of the offshore platforms. They showed that the use of such devices improves the passive control of the structure.

Although the use of energy dissipation systems significantly controls the dynamic response of the structures, several attempts have been done to optimize the controlling effects of energy dissipation systems on the dynamic response of the structures. To do this, various studies investigated the role of different configurations and distributions of the dampers, as well as

brace stiffness, in the dynamic mitigation of structures. Depending on the structure type, these studies can be listed into two main classes: 1) studies on the dynamic response of conventional structures and 2) studies on the dynamic response of offshore structures (marine environment).

Regarding the conventional structures, Constantinou et al. [20] investigated the effects of a toggle-brace damper configuration on the small structural drift. Their experimental results suggest significant increases in the damping ratio, in spite of the use of small size damping devices. Zhang et al. [21] studied the effects of the configuration of a toggle-brace-damper system on the energy dissipation of stiff structures. The results demonstrate that the upper toggle-brace-damper system has the largest displacement magnification factor. Lin et al. [15] studied the effects of Multiple Pounding Tuned Mass Damper (MPTMD) control on the dynamic response of a benchmark tower subjected to earthquake excitations. The results indicated that non-uniformly distributed MPTMD outperforms uniformly-distributed ones. Chen and Chai [2] analyzed the role of brace stiffness on the viscous damper performance, finding that displacement reduction of the structure and the improved performance of brace-viscous damper can be achieved by increasing both the brace stiffness and the damping coefficient of the viscous damper. Dou et al. [22] numerically studied the effects of a tuned liquid damper (TLD) in mitigating the nonlinear vibration of the elastic supporting structural platform (SSP) by varying the mass and TLD to the SSP frequency ratio. Their results proved that the maximum lateral displacement is significantly decreased and the optimal values of mass ratio and frequency ratio were found to be 2% and 1%, respectively.

With reference to offshore structures, several studies investigated the dynamic response of offshore jacket platforms with and without brace-viscous damper system. Elshafey et al. [23] studied the free and forced dynamic responses of a scale jacket platform model in air and water with no viscous dampers. Further, they developed a finite element model and found a good agreement between the experimental and numerical description of the model's dynamic responses. Tabeshpour and Janbazi Rokni [24] numerically studied the effects of brace-viscous damper system with diagonal configuration on the vibration control of jacket platforms under the action of wave loads. Further, they analyzed the conventional arrangements of viscous dampers needed to achieve the optimal one. Janbazi Rokni and Tabeshpour [25] analyzed the wave-induced spectral fatigue of jacket platform equipped with viscous dampers. Further, they applied various distributions of viscous dampers to achieve the optimal one. Hokmabadi et al. [26] studied the efficiency of a combined novel Magneto-Rheological Tuned Liquid Column Gas Damper (MR-TLCGD) in dissipating the dynamic response of a three dimensional fixed offshore jacket platform under both wave and

earthquake excitation. The results of their study revealed the capability of the TLCGD system in reducing the structural vibration. Enferadi et al. [27] studied the impacts of SMA (shape memory alloys) on the dynamic response control of offshore jacket platforms. The results of their numerical simulations revealed that the dynamic response of platforms under the action of an extreme regular wave is enhanced by the application of an optimized SMA with constant-geometry SMA bars. Arjmandi and Heidari [28] studied the capability of a combined viscous damper-rubber bearing base isolation system to control the dynamic response of the Resalat oil platform located in the Persian Gulf under the action of irregular waves modelled through the Jonswap spectrum. To do this, they studied the platform in two different conditions: (1) the platform with rubber bearing isolator only and (2) the platform equipped with the rubber bearing isolator plus viscous dampers. The results proved that the implementation of viscous damper enhanced the controlling effects of the dissipation system.

The above-mentioned studies have provided valuable information on the use of viscous dampers with various configurations and distributions for both offshore and onshore structures. However, the performances of brace-viscous damper systems with various configurations of viscous dampers, as well as brace stiffness, have not been compared for a specific jacket platform. In other words, there is a gap in conducting a study that simultaneously investigates all the effects of viscous dampers' configurations (i.e. chevron, toggle, and diagonal) and distributions (i.e. uniform or non-uniform), as well as brace stiffness, on the dynamic response mitigation of offshore jacket platforms. Hence, we study the joint effects of a combined brace-viscous damper system, accounting both for the effects of various damper configurations and distributions and for a wide range of brace stiffness.

A fundamental tool for the analysis is the finite element ANSYS package. ANSYS has been successfully applied in the simulation of the dynamic response of various structures, among which the seismic control analysis of railway bridge strengthened with viscous dampers [29], the analysis of nonlinear viscous dampers implemented in long-span cable-stayed bridges [30] and the dynamic response control of offshore platforms based on outrigger damping systems [31]. Such good performances suggest use of ANSYS also for the numerical simulation of the dynamic response mitigation of offshore jacket platforms.

The main aim of our contribution is to analyze the effects of the damper configuration and brace stiffness on the performance of brace-viscous damper systems to be implemented in an offshore jacket platform to control the base shear force and displacements of a platform forced by random ocean waves. Further, using the results of the numerical simulations, we propose the spatially-optimized distribution of the brace-viscous damper system.

The paper is structured as follows: Section 2 gives a detailed overview of the impact of various brace-damper configurations (chevron, diagonal, and toggle) and brace stiffness on the dynamic response of the jacket platform. The modelling approach is described in Section 3. The results are presented and discussed in Section 4, which is followed by the summary and conclusions in Section 5.

2. Brace-viscous damper governing variables

Since the present paper focuses on the application of viscous dampers in offshore jacket platforms, only the effect of the brace-viscous damper system on the dynamic response mitigation has been discussed. Viscous dampers dissipate energy by means of the movement of the piston through a highly viscous fluid, and the damping force is out-of-phase with the viscous damper deformation [20]. The force provided by viscous dampers (Eq. 1) always resists against the structure motion and is proportional to the relative velocity between the ends of the damper [32]:

$$F_D(t) = C_D |\dot{U}(t)|^N \text{sgn}(\dot{U}(t)) \quad (1)$$

where $F_D(t)$ is the force generated by the damper, C_D is the damping coefficient depending on pressure difference, N is a constant depending on the orifice shape and ranging from 0.3 to 1.95, $\dot{U}(t)$ is the axial velocity of the damper piston, t is time, and $\text{sgn}(\cdot)$ is the sign function.

As seen from Eq. (1), the viscous dampers resistant forces are directly related to their axial velocity, which depends on their amplitude of displacement [33,34]. Therefore, the performance of viscous dampers (the resistant force generated by the viscous damper) depends on their axial velocity:

$$\dot{U}(t) = A_0 \frac{2\pi}{T} \cos\left(\frac{2\pi}{T} t\right) \quad (2)$$

in which T is the period of the damper piston displacement, and A_0 is the amplitude of the damper displacement.

According to Eq. (1), the force generated by a viscous damper ($F_D(t)$) is directly proportional to its velocity ($\dot{U}(t)$). $F_D(t)$ increases with $\dot{U}(t)$ until $F_D(t)$ reaches its maximum value. In viscous dampers used in structures, $\dot{U}(t)$ is not so large to produce the maximum $F_D(t)$ because the interaction between the viscous damper, brace and structure reduces the $\dot{U}(t)$. The most efficient performance of a brace-viscous damper system is achieved when the viscous damper axial velocity ($\dot{U}(t)$) reaches its maximum value. In order to accomplish the

most efficient brace-viscous damper system, we analyze, in the following sections, the various governing parameters, such as brace stiffness and viscous damper configurations.

2.1. The ratio of brace stiffness to the damping coefficient (K_b/C_D)

Due to the axial strains in a brace and the brace-damper interaction, a reduction in the stiffness of the braces (K_b) reduces the axial displacement of the damper and thus the dissipative effect of the damper. Furthermore, an increase in the flexibility of the braces leads to an increase in the phase difference between the damper and frame displacements. The shear forces of stories reach their maximum when such relative displacement between the damper and the frame is at its peak value. Therefore, if a phase difference exists between the displacements of the viscous damper and frame, the displacement of the viscous damper ($U(t)$) does not become zero at the maximum drift of the stories ($X(t)$) and, because of this, it produces an excessive shear force. The produced shear force has a negative impact on the performances of the damper. It is, therefore, appropriate to produce a damping force which is proportional to the viscous damper velocity ($\dot{U}(t)$) and 90 degrees out of the base shear forces phase (proportional to the frame displacement ($X(t)$)). To achieve this, it is better to design a system in which the damper and the frame displacements have the same phase. As a result, when $X(t)$ has its maximum value, the viscous damper forces ($F_D(t)$) become zero and there is no excessive shear force.

In this case, the damper speed is 90 degrees out of phase with the frame displacement and the maximum damping forces occur when the frame shear force becomes zero. This kind of phase differences can be reduced by increasing the ratio of the brace stiffness (K_b) to the damper damping coefficient (C_D). Figs. 1 and 2 show the phase difference resulting from various braces' stiffness, for small (Fig. 1) and large (Fig. 2) values of K_b/C_D , respectively. As shown, the damper displacements are significantly less than the frame displacements when $K_b/C_D = 2.52$. However, the frame and damper displacements have the same values $K_b/C_D = 25.3$. In summary, the more the ratio of the brace stiffness to damping coefficient increases (K_b/C_D), the more the brace deflection decreases and, as a result of this, the damper axial displacement becomes large and, finally, the force generated by the damper grows.

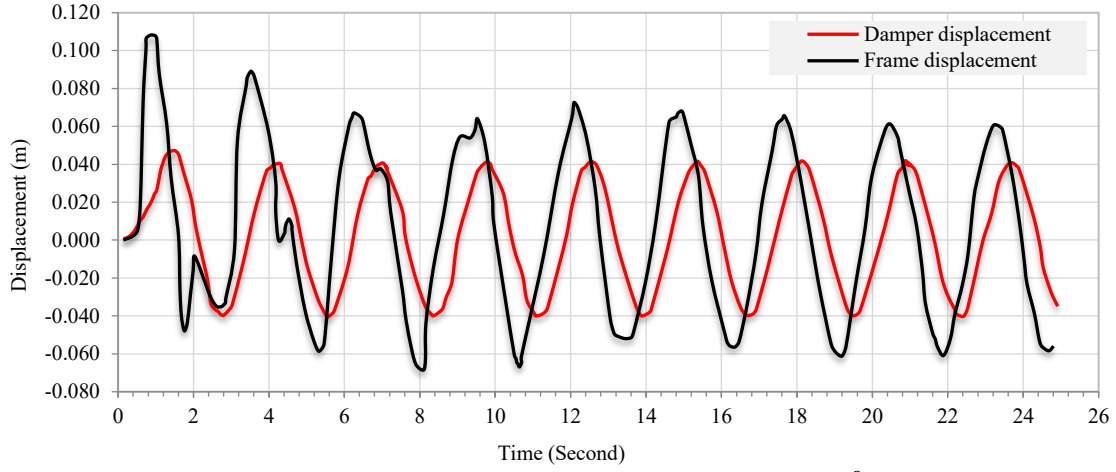


Fig. 1. The phase difference between damper axial displacement and frame displacement ($A_b=10 \text{ cm}^2$, $C_D=10000 \text{ Nm/s}$, $K_b/C_D=2.52$)

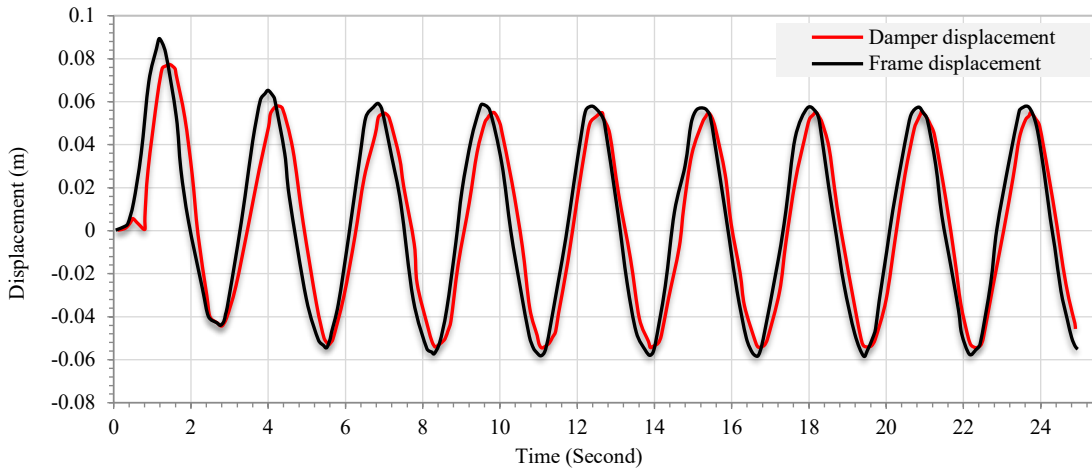


Fig. 2. The phase difference between damper axial displacement and frame displacement ($A_b=50 \text{ cm}^2$, $C_D=5000 \text{ Nm/s}$, $K_b/C_D=25.3$)

2.2. Damper configuration

In addition to the brace stiffness and damper properties (damping coefficient), the performances of brace-viscous damper systems can be improved by optimizing their configuration and distribution in a frame. If the axial displacement of a viscous damper is more than the axial displacement of the story where the damper is installed, the axial speed of the viscous damper and, as a consequence, the force along the axis of the damper ($F_D(t)$) increases. When the amplitude of a viscous damper axial displacement is maximum during the structure vibration, the damper achieves its best performance; otherwise, only a portion of the damper capacity is used. The axial displacement of the damper that is installed in a story can be described as:

$$U(t) = m_f X(t) \quad (3)$$

where $U(t)$ is the relative displacement of the viscous damper, $X(t)$ is the structure displacement, and m_f is a magnification factor. The latter, which gives the damper axial

displacement to story displacement ratio, is larger or smaller than one depending on the damper configuration in the frame. Similarly, $F_h(t)$ which relates to the horizontal component of the force exerted by the viscous damper ($F_D(t)$) on the frame can be described as:

$$F_h(t) = m_f F_D(t) \quad (4)$$

The impact of a viscous damper configuration on the magnification factor and on the axial force exerted by the damper on the frame (see Eq. (4)) is not negligible. Since the magnification factor depends on the configuration of the viscous damper, the next subsections focus on the effects of three different configurations, diagonal, chevron and toggle configurations, on the performances of viscous dampers.

2.2.1. Diagonal configuration

As shown in Fig. 3A, in this configuration, the damper is located along the brace axis and the magnification factor can be calculated using Eq. (5).

$$m_f = \cos(\theta) \quad (5)$$

where θ is the inclination angle of the damper.

In the diagonal configuration, the differential equation of motion, accounting for the interaction between the damper and brace, is as follows:

$$m\ddot{X}(t) + (C_D + \cos(\theta) C_{Db})\dot{X}(t) + (K + K'_{vb})X(t) = F_{ext}(t) \quad (6)$$

in which m is the mass of the structure, $\ddot{X}(t)$ is the second time derivative of the structure displacement, C_D is the damping coefficient, $\dot{X}(t)$ is the first time derivative of the structure displacement, K is the structure stiffness, K'_{vb} is the energy distribution capacity of brace-viscous damper system, and $F_{ext}(t)$ is the external excitation force.

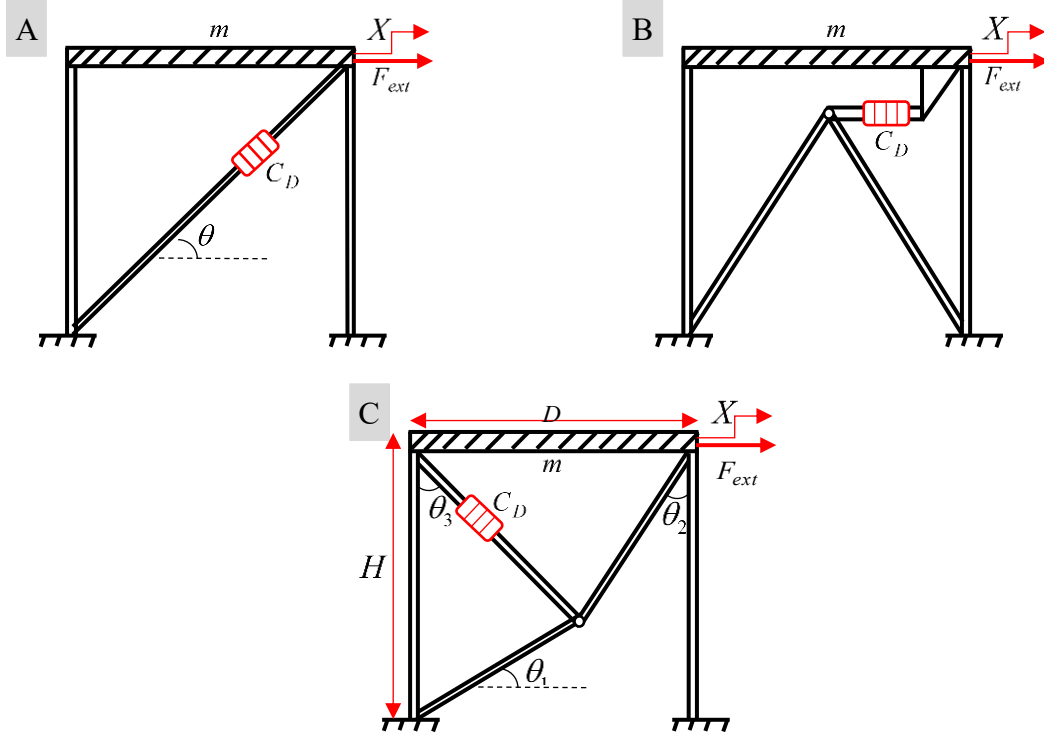


Fig. 3. The various configurations of a viscous damper; (A) Diagonal configuration [35], (B) Chevron configuration [35], (C) Upper Toggle Brace Damper (UTBD) configuration [20]

2.2.2. Chevron configuration

As shown in Fig. 3B, in this configuration, the damper is installed in the upper section of the braces and parallel to the story level. The inclination of the damper in the chevron configuration is zero, and then the magnification factor is equal to one. This means that the axial displacement of the damper and story drifts have the same values. The motion equation, which accounts for the interaction between the damper (with chevron configuration) and the brace is:

$$m\ddot{X}(t) + (C_D + C_{Db})\dot{X}(t) + (K + K'_{vb})X(t) = F_{ext}(t) \quad (7)$$

2.2.3. Toggle brace damper (TBD) configuration

In the toggle brace system, the damper is installed diagonally from its first end-jointed to the beam-column connection and its other end to the brace connection (Fig. 3C). In this case, the magnification factor depends on the angles of both braces and damper (θ_1 , θ_2 , and θ_3). According to Zhang et al. [21], the deformations of the beams are assumed to be negligible in the deriving of the magnification factor. The selection of an appropriate magnification factor is made by imposing the following constraints from the geometric configurations in the TBD system [21]:

$$\theta_1 \leq \tan^{-1}(H/D)$$

$$\begin{aligned} \frac{L_1}{D} &\leq \frac{1}{\cos \theta_1} \\ \theta_2 &= \tan^{-1} \left(\frac{1 - (L_1/D) \cos \theta_1}{(H/D) - (L_1/D) \sin \theta_1} \right) \\ \theta_3 &= \tan^{-1} \left(\frac{(L_1/D) \cos \theta_1}{(H/D) - (L_1/D) \sin \theta_1} \right) \\ L_2 &= \frac{H - L_1 \sin \theta_1}{\cos \theta_2} \end{aligned} \quad (8)$$

where θ_1 is the horizontal angle of the lower brace; H is the inter-story height; D is the frame bay length. L_1 and L_2 are the lengths of the lower and upper toggle braces, respectively. θ_2 is the vertical angle of the upper brace, and θ_3 is the vertical angle of the damper. The magnification factor is then obtained, as suggested by Zhang et al. [21]:

$$mf = \frac{\sin \theta_2}{\cos(\theta_1 + \theta_2)} \cos(\theta_3 - \theta_1) + \sin \theta_3 \quad (9)$$

Inspection of Eq. (9) reveals that the magnification factor attains very large values as $\theta_1 + \theta_2 \rightarrow 90^\circ$. The 90° TBD configuration is useless when the toggles form a straight element that acts as a brace. Of significance is the sensitivity of the magnification factor on changes in the geometry. Practical configurations are those for which small changes in the geometry do not cause large changes in the magnification factor. Such considerations limit the practical values of the magnification factor in the range of about 2–5 [21].

3. Numerical analysis

3.1. Case study description

In order to investigate the effects of configuration, distribution, and brace stiffness on the performances of brace-viscous dampers system, a scaled model of a fixed offshore jacket platform, studied experimentally and numerically by Elshafey et al. [23], has been implemented in ANSYS (Fig. 4). The prototype structure is a four-legged jacket with a combination of diagonal and V-shape bracings, but it does not implement viscous dampers. Froude scaling was used because of the fundamental role of gravity sea waves and the model fabricated with Acrylonitrile Butadiene Styrene (ABS) pipes, while the deck structure was made of Acrylic sheets with 0.0127m thickness. The main legs, bracings, and deck were constructed using pipes with an external diameter of 0.0254, 0.0111, 0.0127, and 0.0159m, respectively. All pipes had the same thickness of 0.0159m. The total height of the model,

including the deck, was 2.663m. The four legs at the bottom formed a rectangle with dimensions of $1\text{m} \times 0.636\text{m}$. The structure consisted of five levels separated by horizontal bracings. The main legs were slanted from the base up to a height of 1.953m to form a rectangle with dimensions of $0.667\text{m} \times 0.300\text{m}$. The main legs were kept vertical from a height of 1.953m to the top of the deck. The deck had a rectangular shape with a length of 0.966m and a width of 0.600m.



Fig. 4. The scale model of Elshafey et al. [23]

3.2. Finite element model

The numerical representation of the Elshafey et al. [23] platform has been reproduced using the ANSYS software. The main legs of the platform have been modelled using PIPE59 elements, which implement the effects of drag coefficient, added mass, buoyancy force and surface roughness coefficient of the pipes in the modelling process. The parameters responsible to characterize the vibration features in wet and dry conditions have been set as follows: the added mass coefficient $C_M = 1$, the drag factor $C_D = 0.7$, the inertia coefficient $C_I = 1$ and the buoyancy coefficient $C_B = 1$. The deck was modelled using SHELL63 elements, which provide the bending and membrane properties. The MASS21 element was exploited to model the mass of the deck. The latter element has six degrees of freedom (three displacements and three rotations in x, y, z axes). Fig. 5 shows the different configurations of the viscous damper that have been modelled using the ANSYS software in the present study.

3.3. Wave Loading

Since our study focuses on fetch-limited, rather than fully developed sea conditions, the Pierson-Moskowitz and Bretschneider spectra give spectral density which is too small to describe real sea conditions. In these cases, the JONSWAP (Joint North Sea Wave Analysis Project) spectrum is more useful, since the peak of the JONSWAP spectrum is more pronounced, as a function of the γ parameter.

The JONSWAP spectrum we used to simulate wave loads is expressed by the following equation [17]:

$$S(f) = \frac{A}{f^5} e^{-(B/f^4)} \gamma^a \quad (10)$$

in which:

$$A = \frac{5H_s^2 f_0^4}{16\gamma^3} \text{ for } 1 < \gamma < 4$$

$$B = \frac{5}{4} f_0^4$$

$$a = \exp \left\{ \frac{-(f - f_0)^2}{2\sigma^2 f_0^2} \right\}$$

$$\sigma = 0.07 \quad \text{for } f \leq f_0$$

$$\sigma = 0.09 \quad \text{for } f > f_0$$

where $S(f)$ is the spectral energy density, f is the frequency of the waves, γ is the peak enhancement factor, f_0 is the peak frequency of the waves, H_s is the significant wave height, and σ is the width parameter. As shown in Fig. 6, we have used $H_s = 25\text{cm}$ and $f_0 = 0.7\text{Hz}$. Since the jacket platform used as the case study is a scaled-down model of a fixed offshore jacket platform (see Section 3.1 and, for more details, Elshafey et al. [23]), also the wave loading is scaled according to Froude's law. Natural scale dynamics can be retrieved by scaling up the results here proposed.

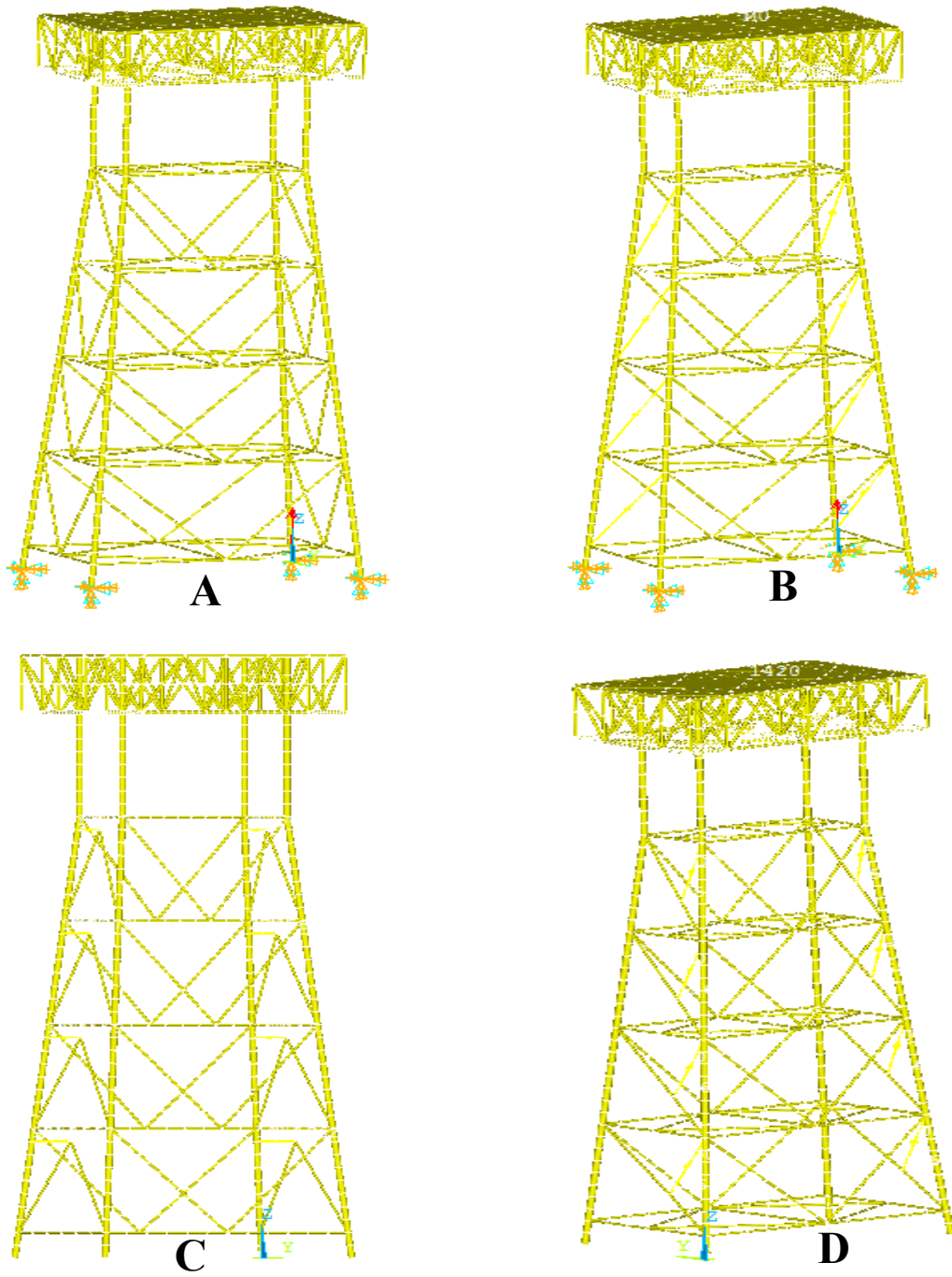


Fig. 5. Finite element model of the offshore jacket platform used in this study with different configurations. (A) without damper ;(B) Diagonal ;(C) Chevron ;(D) Upper toggle brace damper (UTBD)

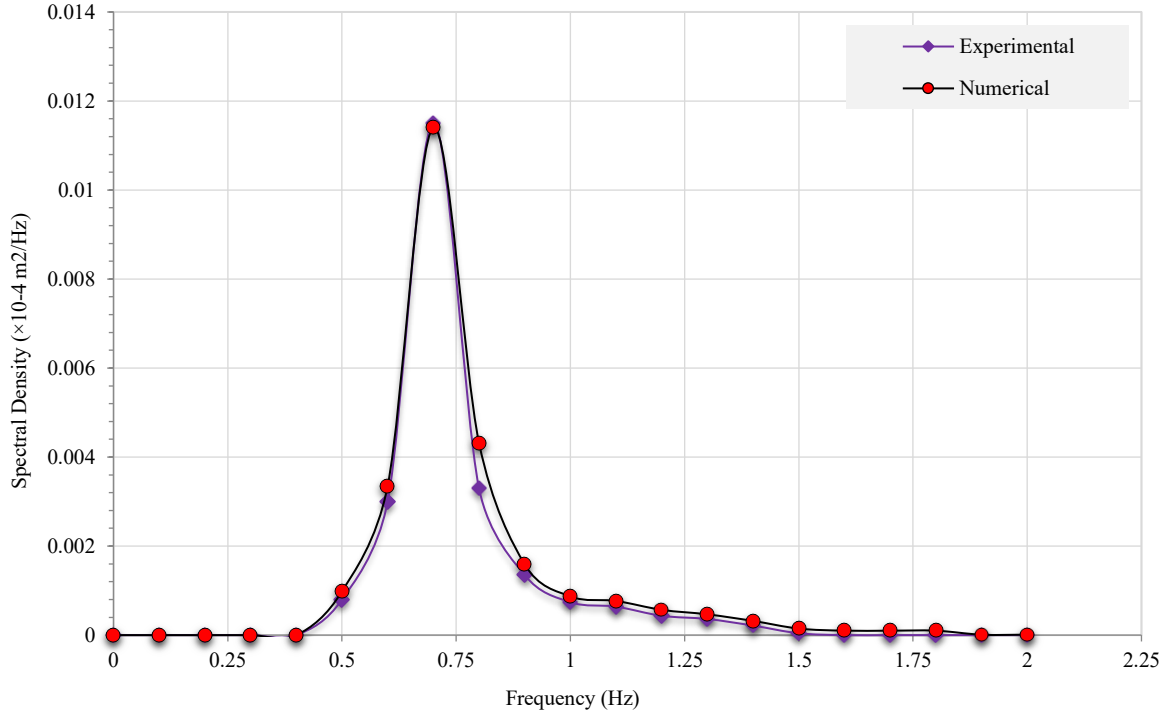


Fig. 6. The spectral density of the waves used in this study ($H_s = 0.25 \text{ m}$, $f_0 = 0.7 \text{ Hz}$) (Elshafey et al. [23])

4. Results and discussion

4.1. Model verification

4.1.1. Verification of the Jacket simulations

The performances of the numerical model have been verified against the experimental and numerical results proposed by Elshafey et al. [23] on the dynamic response of a jacket platform. The left panel of Fig. 7 shows the models of the jacket by Elshafey et al. [23], while the right panel gives its representation in ANSYS. Fig. 8 shows that the normalized acceleration of the deck vibration provided by Elshafey et al. [23] and that computed by ANSYS are very similar. Fig. 9 shows the first five vibration modes (1st to 5th mode) of the jacket platform of Elshafey et al. [23] and the same modes described by the ANSYS simulation. The two sets of results match very well and the vibration modes of the numerical simulations are in line with those of both experimental measurements and numerical simulations by Elshafey et al. [23]. Moreover, the values of 1st to 10th natural frequencies (in the wave propagation direction, i.e. x-direction), for the case of no additional deck mass, from Elshafey et al. [23] and from the present simulations are summarized in Table 1. A simple inspection of the Table 1 reveals that differences between the benchmark data by Elshafey et al. [23] and the simulations of the present study are less than 7.85%.

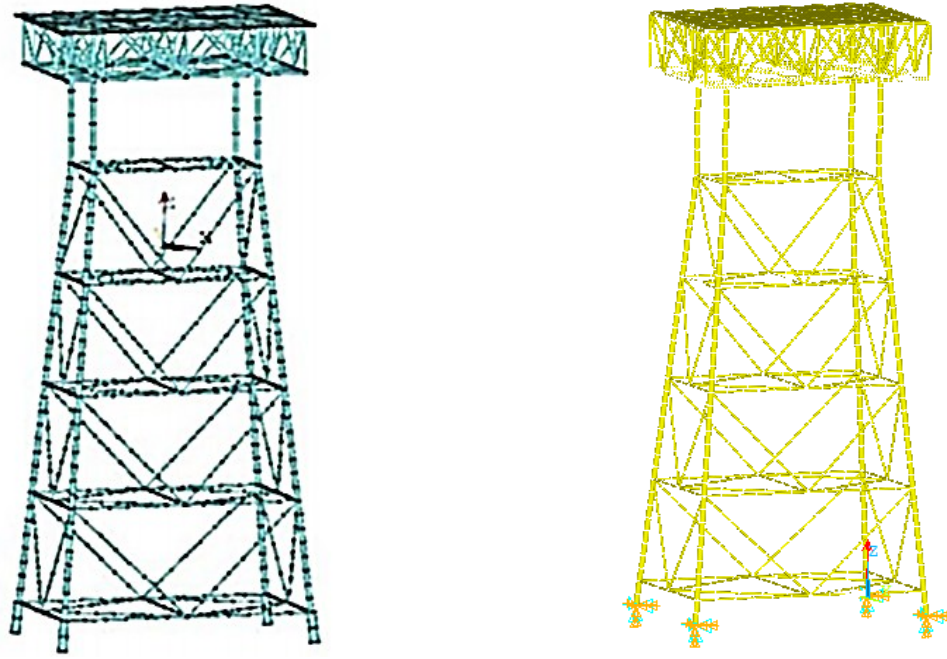


Fig. 7. The finite element model by Elshafey et al. [23] (left panel) and its simulation by ANSYS (right panel)

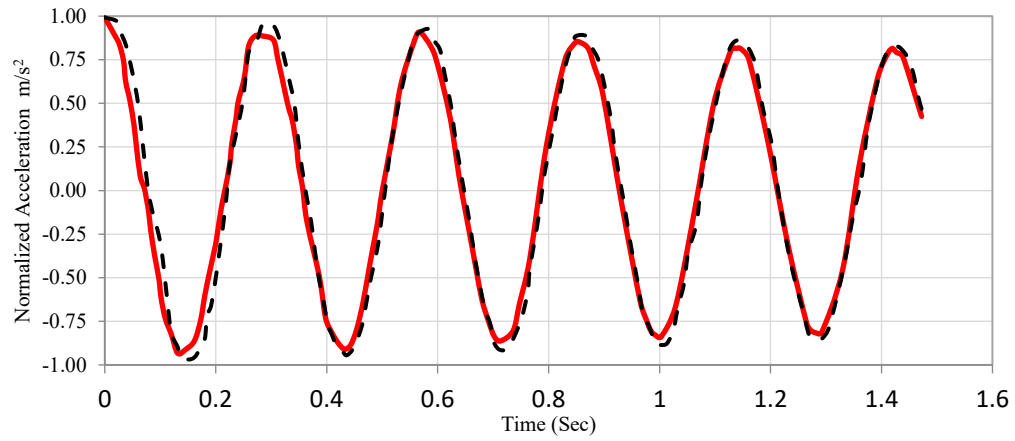


Fig. 8. Normalized vibration acceleration of the deck of the platform in Fig. 7. Data from Elshafey et al. [23] (black dashed line) and the present numerical results (red line).

Table 1. The natural frequencies (Hz) of the jacket platform in the x-direction by Elshafey et al. [23] and the current study

Mode No.	1	2	3	4	5	6	7	8	9	10
Elshafey et al. (2009)	3.566	3.999	4.534	21.838	24.093	27.181	27.604	29.809	30.632	30.979
The present paper	3.563	3.9084	4.5747	20.123	24.958	28.391	28.589	30.94	31.172	31.044
Differences (%)	0.084	2.260	0.898	7.853	3.590	4.452	3.568	3.794	1.763	0.210

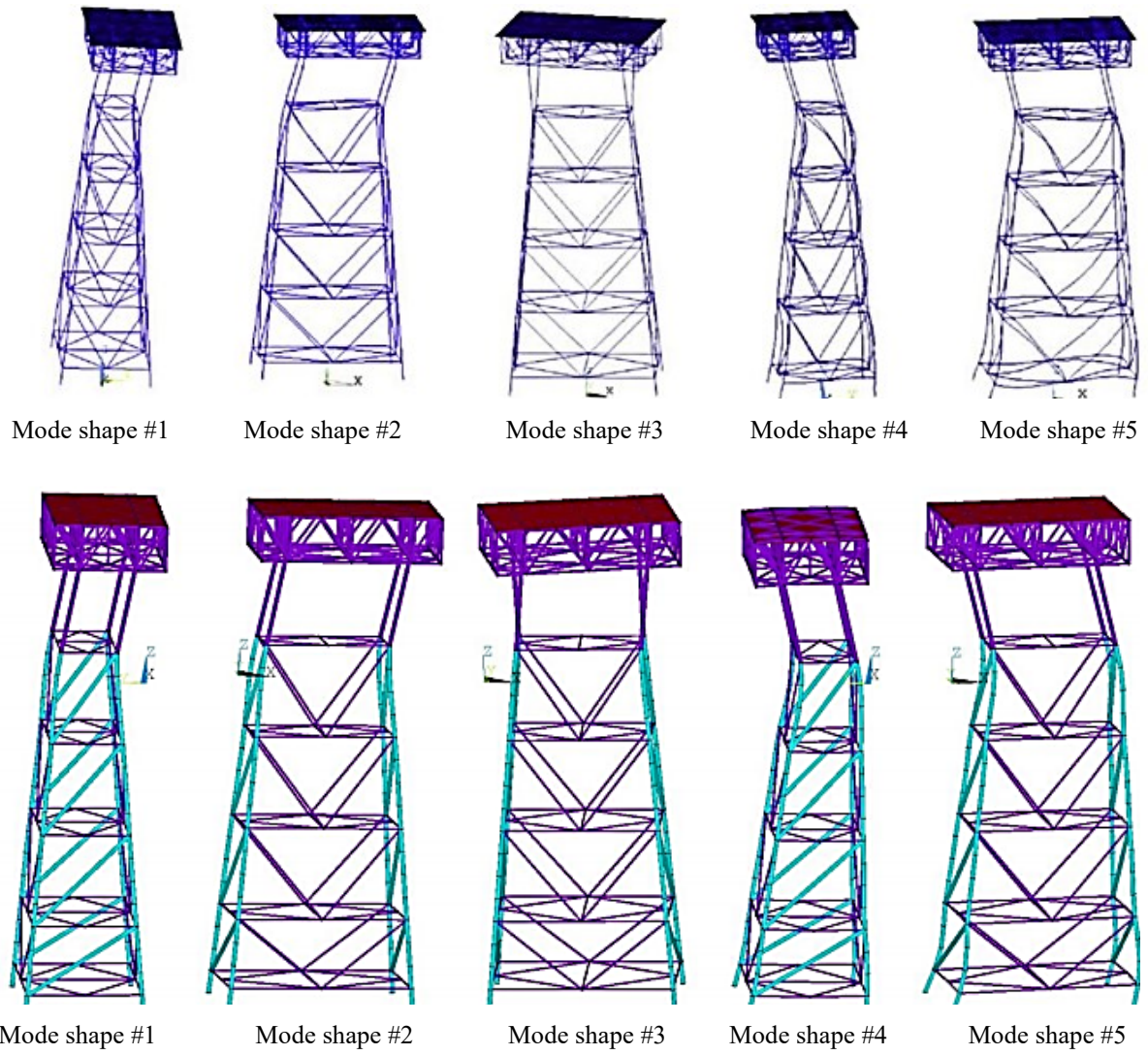


Fig. 9. The first to fifth vibration modes of the jacket platform of Elshafey et al. [23] (upper panel) and the present study (bottom panel)

4.1.2. Verification of viscous damper simulations

In order to develop a model for the viscous dampers, a combined element named “COMBIN14” has been used. Such a massless element can rotate, twist, and axially displace in 1, 2, or 3 dimensions. The viscous damper masses can be added by using the appropriate mass element (e.g. MASS21). To evaluate the performance of our numerical model in describing the viscous damper, the response of a viscous damper simulated by ANSYS has been compared with that of Ou et al. [14]. The damping coefficient $C=153 \text{ KN.S/m}$ and the frequency $f=2.5 \text{ Hz}$, used in the experimental damper by Ou et al. [14], have been used in the present simulations. Fig. 10 shows a comparison between the reference (by Ou et al. [14]) and simulated viscous damper response. It is evident that the response of the simulated viscous damper behaves in agreement with that of the experimental model by Ou et al. [14].

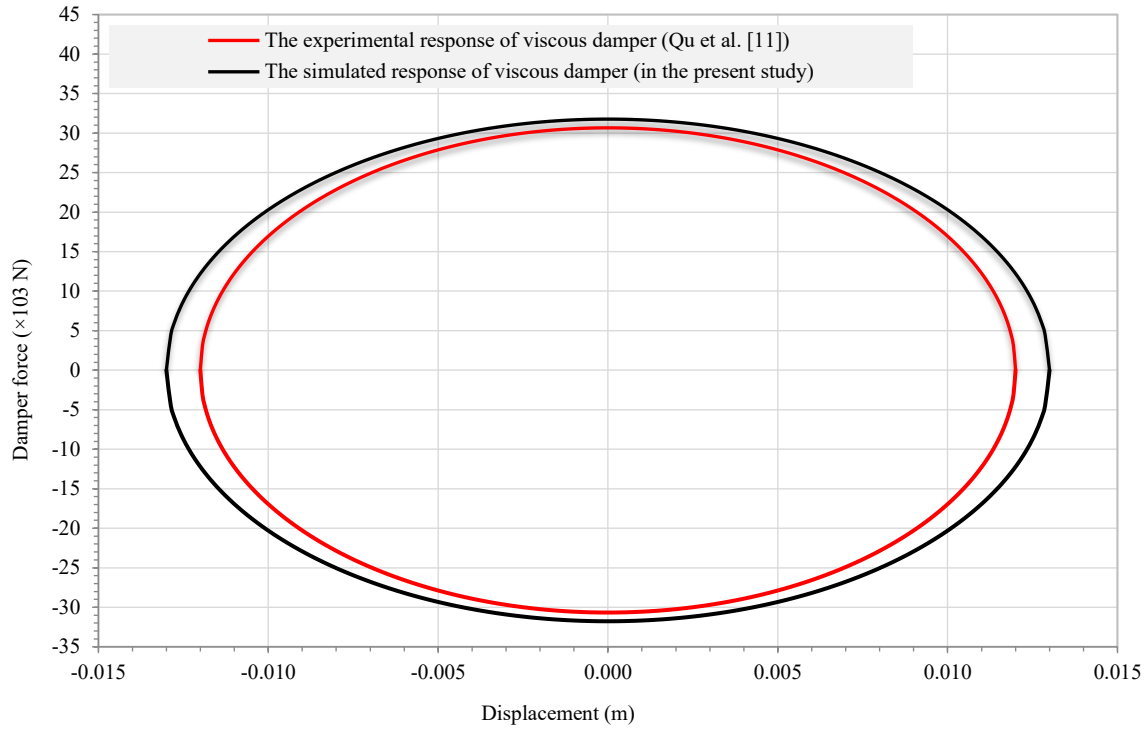


Fig. 10. The response of the simulated viscous damper and the experimental viscous damper by Ou et al. [14] for $f=2.5$ Hz

4.1.3. Verification of the Jacket simulations with diagonal viscous damper

Tabeshpour and Janbazi Rokni [24] studied the effects of viscous dampers on the dynamic response of a field jacket platform known as “oil platform SPD2” under the action of ocean wave loads. Fig. 11 illustrates the 2D numerical representation of the jacket platform studied by Tabeshpour and Janbazi Rokni [24]. The left panel refers to the jacket platform with no viscous dampers and the right panel shows the platform equipped with diagonal viscous dampers. The SPD2 is a wellhead jacket platform installed in Persian Gulf and the water depth in the vicinity of the platform is approximately 65.7m. The natural period of this platform is 1.62 seconds. In the Persian Gulf the dominating wave spectrum is the JONSWAP spectrum and the significant wave height and period are of about 5.83m and 7.10s, respectively. To develop the ANSYS numerical simulations, the drag and inertia coefficients have been set to 0.7 and 2, respectively. Further, pipes have been modelled using “Pipe 59” elements, while the mass of the deck has been modelled using “Mass 21” element and the viscous damper simulated by means of “Combine 14” elements. Fig. 12 illustrates the PSDF of the deck displacement with and without viscous dampers based on the results by Tabeshpour and Janbazi Rokni [24] and our ANSYS simulation. It is clear that our numerical results are completely in line with the numerical results of Tabeshpour and Janbazi Rokni [24]. Table 2 summarizes the standard deviation of deck displacements of the SPD2 platform resulting from our ANSYS simulations and Tabeshpour and Janbazi [24]’s models for two

cases: (1) with no viscous dampers and (2) with viscous dampers, as shown in Fig. 11. The differences between the standard deviations of deck displacements are negligible, approximately 1.45% for the case of no viscous dampers and 2.59% for the case with viscous damper. The latter finding proves that ANSYS can produce numerically sound results in the modelling of a jacket platform equipped with diagonal brace-viscous dampers.

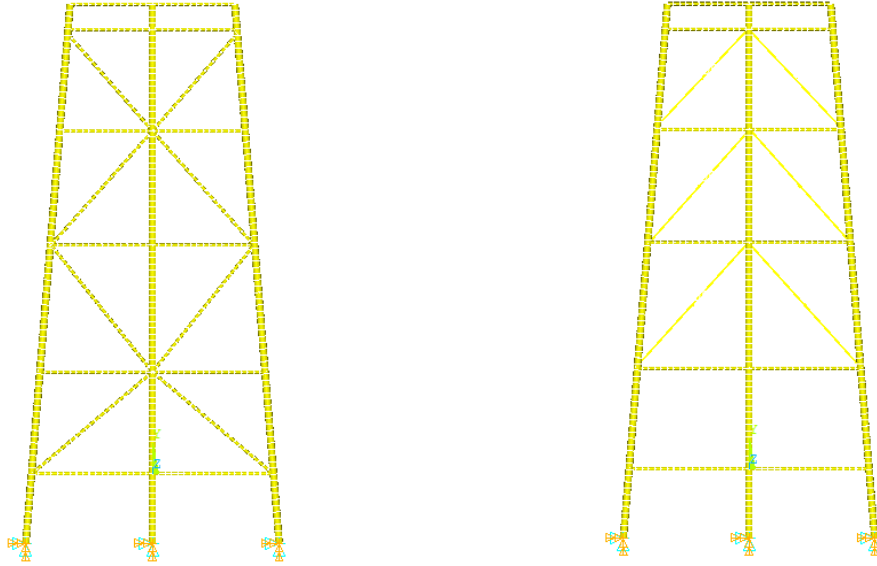


Fig. 11. Numerical representation of the SPD2 jacket platform by Tabeshpour and Janbazi [24]: with no viscous dampers (left panel) and with diagonal viscous damper (right panel)

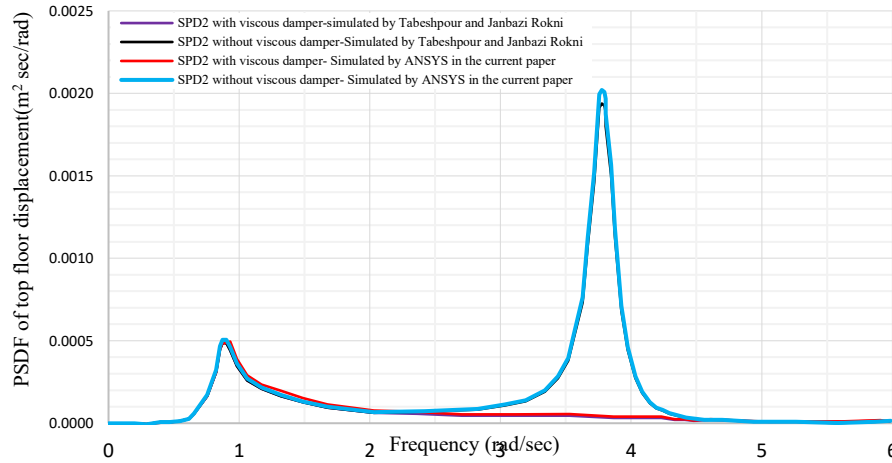


Fig. 12. Variation of the PSDF of deck displacement with and without dampers (SPD2 platform) against frequency based on Tabeshpour and Janbazi [24] and the current paper (ANSYS) numerical results.

Table 2. Comparison between the ANSYS and Tabeshpour and Janbazi simulation results for the SPD2 platform displacements

Numerical approach	Platform status	Standard deviation of deck displacements (m)	Reduction percentage in displacements in comparison to without damper case (%)	Difference between ANSYS and Tabeshpour and Janbazi results (%)
Tabeshpour and Janbazi Rokni [24]	Without viscous damper	0.0311	-	
	With viscous damper	0.0186	40.20	
Present ANSYS simulations	Without viscous damper	0.0315	-	1.45
	With viscous damper	0.0189	39.16	2.59

4.1.4. Verification of viscous damper with toggle configuration

To verify the implemented finite element model in simulating the toggle viscous damper behavior, a steel frame prototype, whose dynamic response is investigated by Soong and Dargush [36] and equipped with toggle viscous dampers, has been used. They experimentally analyzed such structure as forced by the 1940 El Centro earthquake excitation. Fig. 13 shows the experimental (left) and numerical (right) models of the considered frame.

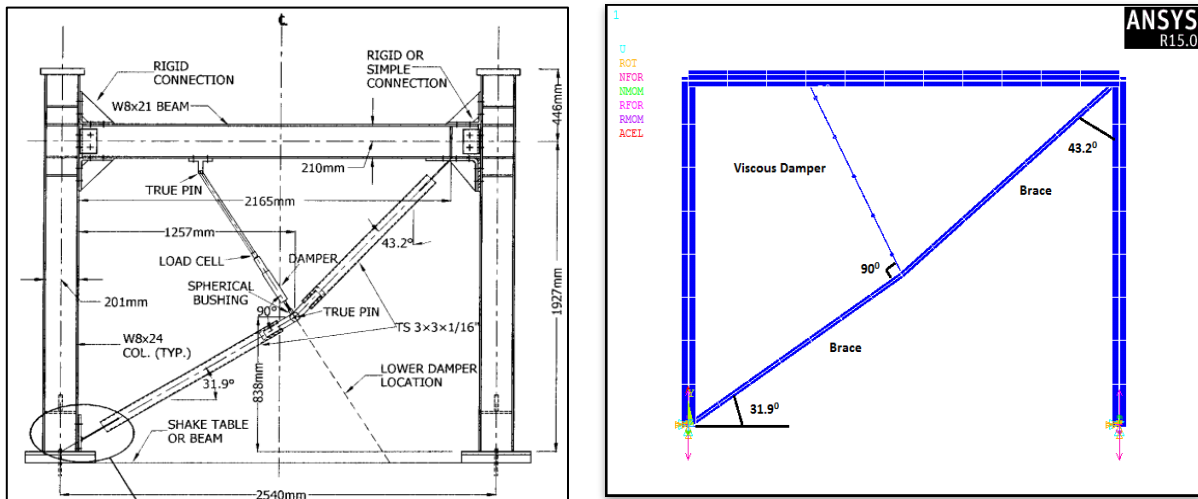


Fig. 13. The experimental model of Soong and Dargush [36] (left panel) and its numerical simulation in ANSYS (right panel)

As illustrated in Fig. 14, the joint acceleration and drift responses resulting from the experimental study of Soong and Dargush [36] reproduced very well by the numerical model in use.

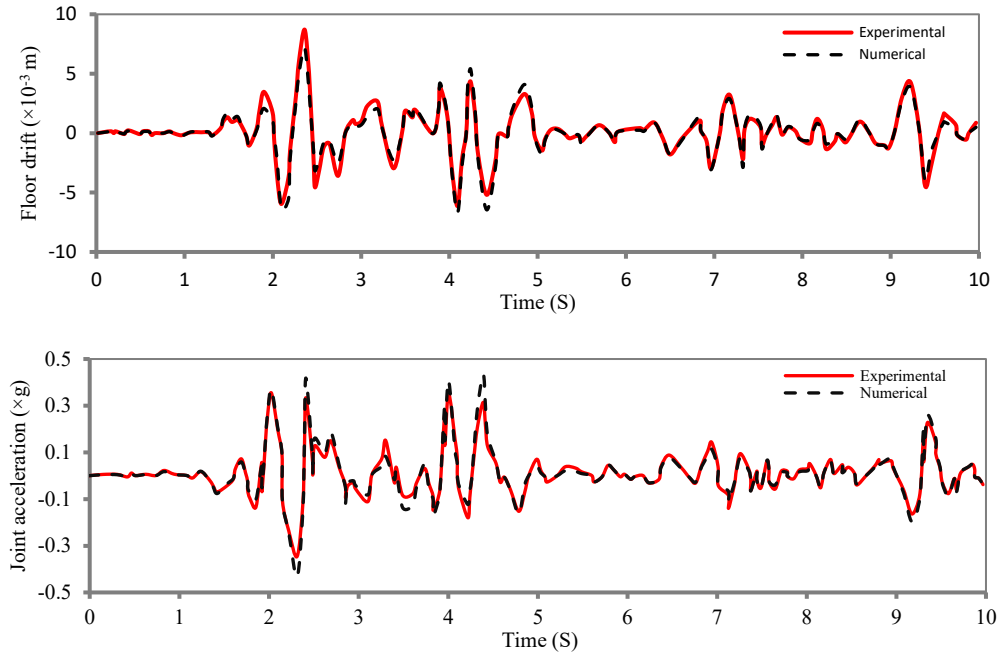


Fig. 14. Joint acceleration and story drift resulted from the experimental study of Soong and Dargush [36] and the numerical model in use.

4.1.5. Verification of viscous damper with chevron configuration

To validate the finite element model performance in simulating the behavior of viscous dampers with chevron configuration, the small scale three-story steel frame of Rama Raju et al. [37] has been used as suitable benchmark. In order to implement the model in ANSYS, the element “Beam188” has been used for beams, columns, and braces. This is a linear beam element and has six degrees of freedom at each node in the three-dimensional space. The degrees of freedom at each node are translations in x, y, and z directions, and rotations about the x, y, and z directions. Warping of cross sections is assumed to be unrestrained. The elements “Mass21” and “Combine14” are exploited to numerically simulate stories mass and viscous dampers, respectively. The benchmark model (experimental model) and its representation in ANSYS are shown in Fig.15. The damping coefficient of all the viscous dampers is set to 0.28 and the results are achieved by means of the spectrum response method. The results of maximum lateral displacements and shear forces at each story are summarized in Table 3. The errors between the benchmark and numerical results are presented in terms of difference rate. For detailed information on benchmark model and applied dynamic loads the reader is referred to [37].

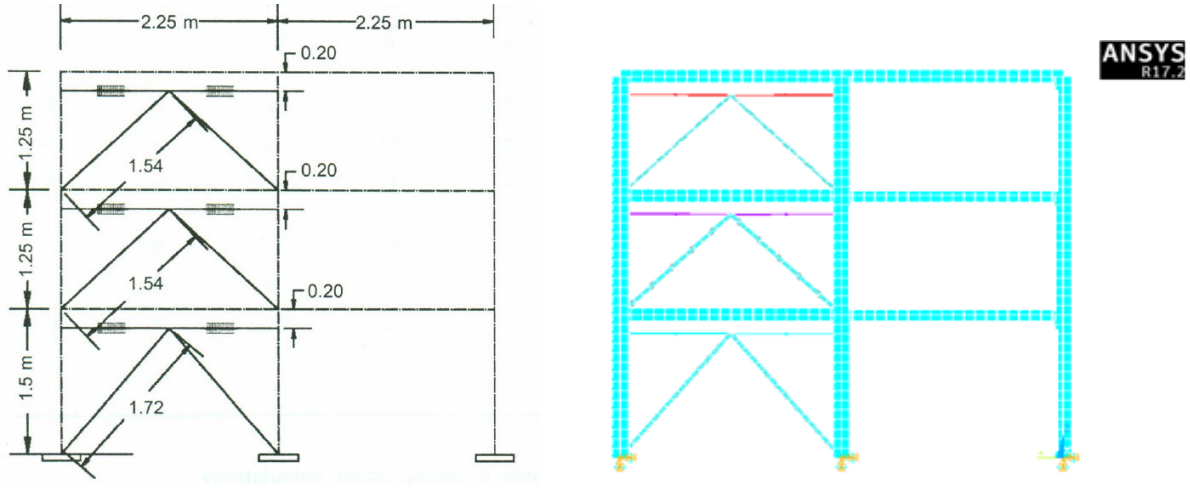


Fig. 15. The experimental setup [37] of the three-story frame with chevron viscous dampers and their numerical simulations developed in the current paper (cyan figure)

Table 3. Maximum displacements and shear forces of the benchmark model of Rama Raju et al. [37] and its numerical simulation in the current paper (viscous damper configuration is chevron)

Story	Damping coefficient ($\times 10^3$ N.s/m)	Benchmark		Numerical solution		Error (difference rate) between benchmark and numerical solution	
		Shear force ($\times 10^3$ N)	Maximum displacement ($\times 10^{-3}$ m)	Shear force ($\times 10^3$ N)	Maximum displacement ($\times 10^{-3}$ m)	Shear force error (%)	Maximum displacement error (%)
3	40	41.82	14.69	41.11	13.86	1.727	5.988
2	95	88.79	11.82	87.97	11.02	0.932	7.260
1	145	133.96	7.25	133.24	6.97	0.540	4.017

4.1.6. Verification of viscous damper with diagonal configuration

To verify the viscous damper simulations in ANSYS, a steel frame with three stories has been forced by the 1940 El-Centro earthquake excitation. Fig. 16 illustrates the experimental model of the mentioned structure at a 1:4 scale as reproduced by Constantinou and Symans[33]. The seismic response of this building has been investigated for 0, 2, 4 and 6 diagonal viscous dampers. The simulated models of the structure with such viscous dampers are illustrated in Fig. 16 with cyan color. The total mass of the building is 2900 kg which has been distributed equally between the stories.

Table 4 summarizes the results of the experimental study conducted by Constantinou and Symans [33] and of the numerical simulations run with the model implemented in ANSYS. The ANSYS model results match very well the benchmark data, this giving confidence in the use of ANSYS also for this specific type of damper.

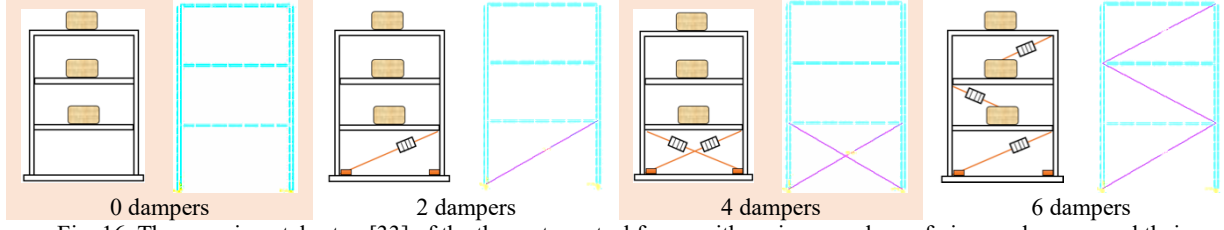


Fig. 16. The experimental setup [33] of the three-story steel frame with various numbers of viscous dampers and their numerical simulations developed in the current paper (cyan figures)

Table 4. The Constantinou and Symans [33] experimental and ANSYS results for the three-story steel frame

Number of dampers	Peak drift of the story height (%)		Peak base shear weight		Difference rate (percentage) between the benchmark and numerical solution (%)	
	Results of the numerical model	Results of the experimental study [29]	Results of the numerical model	Results of the experimental study [29]	Peak drift of the story height	Peak base shear weight
0	0.295	0.290	1.498	1.500	1.72	0.001
2	0.196	0.179	0.865	0.775	9.50	0.12
4	0.159	0.116	0.660	0.539	37.07	0.22
6	0.138	0.105	0.510	0.477	31.43	0.07

4.2. Effect of the brace area on the performances of the viscous damper

In Section 2.1 we highlighted that for a constant brace area the damper configuration can play an important role in the vibration reduction process. Fig. 17 shows the time histories of displacements, which are seen to have a random nature. As indicated, the toggle configuration mitigated the structure response slightly better than the other configurations. The standard deviation of the displacements of the platform deck:

$$\sigma_{sd} = \sqrt{\frac{\sum_{i=1}^M (X_i - \bar{X})^2}{M}} \quad (11)$$

provides useful information for 1) a clearer explanation of the effects of the brace area on the platform dynamic response (see also Elshafey et al. [23]), 2) the comparison of the performance of various brace-viscous damper system configurations. The time history analysis we have carried out implies the presence of many modes (i.e. frequencies), each with its own top floor displacement X_i . In Eq. (11), σ_{sd} , X_i , $\bar{X}$ and M are the standard deviation of top floor displacements, top floor displacement, mean of displacements at all frequencies and number of all displacements (or frequencies), respectively.

Table 5 and Fig. 18 show that for a specific configuration and constant damping coefficient, an increase in brace area, which is equivalent to an increase in brace stiffness, decreases the standard deviation of the platform displacement. It should be noted that the standard deviations of displacements associated with toggle configuration are less than those of chevron and diagonal configurations for various values of brace area. However, for a reference damping coefficient of 500 N.m/s, a 54% increase in the brace area (from 42 to

91.8 mm²) results in a 21.26%, 38.61%, and 17.57% reduction in the structure displacement response for the diagonal, chevron, and toggle configurations, respectively.

Table 5. Influence of the brace area (brace stiffness) on the performance of viscous dampers in terms of vibration reduction (reference damping coefficient of 500 N.s/m)

Brace Area ($\times 10^{-6}$ m ²)	The standard deviation of platform displacements ($\times 10^{-3}$ m)		
	Chevron configuration	Toggle configuration	Diagonal configuration
42.0	0.17205	0.07732	0.21791
46.9	0.16603	0.07578	0.21325
51.9	0.15967	0.0742	0.20451
56.9	0.15317	0.07258	0.19625
61.9	0.14625	0.07109	0.19112
66.9	0.13927	0.06963	0.18744
72.0	0.13235	0.06819	0.18361
76.8	0.12547	0.06695	0.18101
81.9	0.11865	0.06572	0.17984
86.8	0.11206	0.06458	0.17910
91.8	0.10562	0.06373	0.17158

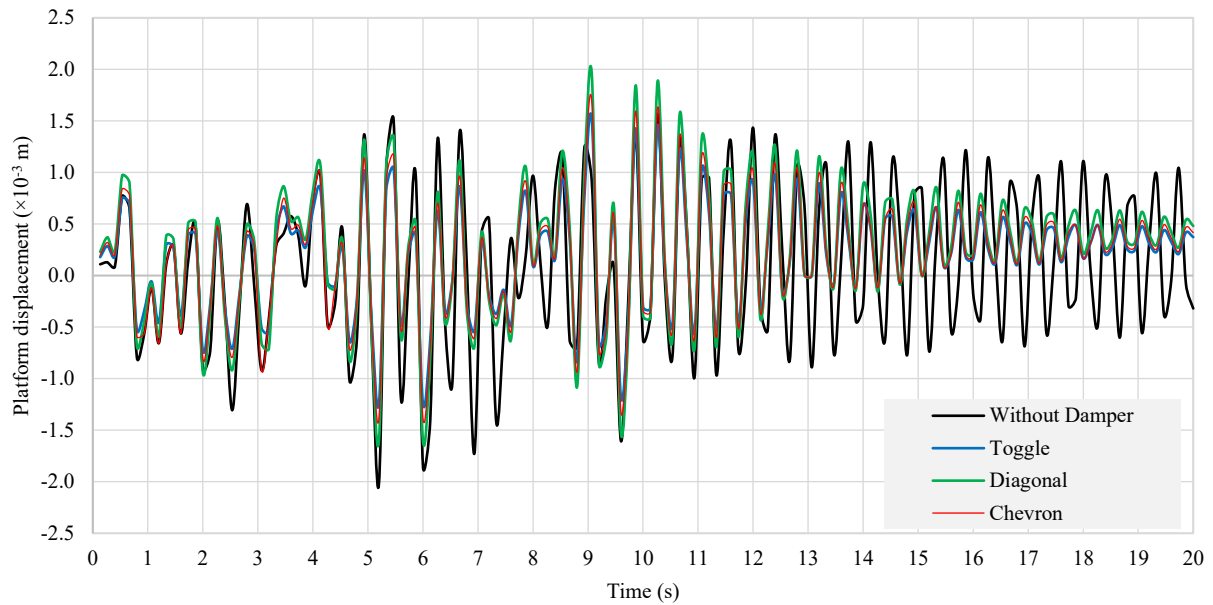


Fig. 17. Time histories of platform displacements without/with various configurations of viscous damper (brace area of 91.8×10^{-6} m² and reference damping coefficient equal to 500 N.s/m)

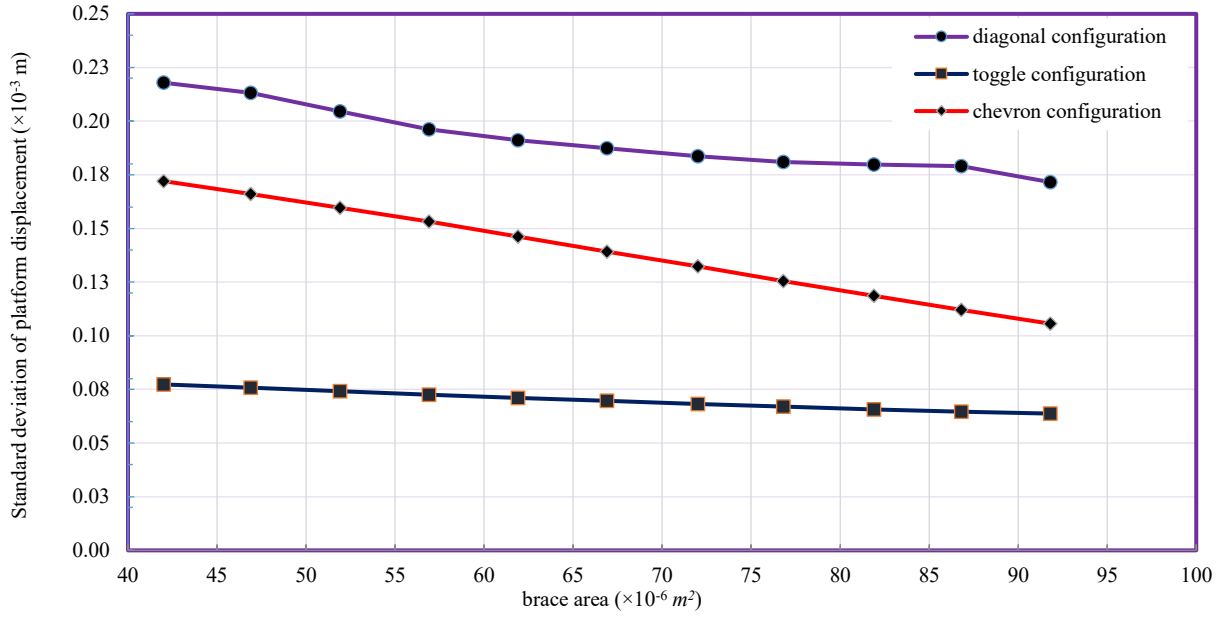


Fig. 18. The influence of the brace area on the performance of viscous dampers of various configurations (reference damping coefficient equal to 500 N.s/m)

What given in section 2 seems to be confirmed for all the damper configurations and our numerical model proves that the brace stiffness (or brace area) directly influences the efficient performances of viscous dampers. In other words, an increase in brace area (or brace stiffness) reduces the interaction between the viscous damper and brace. As a result of this, the axial velocity of the viscous damper ($\dot{U}(t)$) and consequently, the resistant force generated by the viscous damper ($F_D(t)$) increases. The viscous damper resistant force is directly proportional to the efficiency of its performance. According to Table 5, the minimum standard deviation of the platform displacement in the toggle configuration is 0.06373 mm while it is 0.10562 mm and 0.17158 mm for the chevron and diagonal configurations, respectively.

4.3. Effect of damping coefficient on the base shear force

The main aim of using dampers in structures is the reduction of displacements and structural deflections. Since jacket platforms are secured to the seafloor, their legs undergo significant base shear. By using viscous dampers in jacket platforms, much of the base shear can be dissipated. The amount of dissipation depends on several factors, including damper configuration, brace area (see also Section 2.1), and the damping coefficient. It is evident that an increase in the damping coefficient increases the value of the damping force and, as a consequence, base shear forces and displacements reduce. However, we focus on the relation between the damping coefficient and the base shear force. To do this, the various damping coefficients are considered for each specific configuration. Table 6 and Fig. 19 give the

variations of maximum base shear force against the variations of the damping coefficient for diagonal, chevron, and toggle configurations. For all the damper configurations, an increase in the damping coefficient leads to a base shear reduction. For instance, in the case of the chevron configuration, the maximum reduction of the base shear occurs when the damping coefficient is of 3500 N.s/m. Also, the maximum reductions of the base shear force for increasing damping coefficient are 6.073%, 2.16%, and 0.215% for the toggle, chevron, and diagonal configurations, respectively. However, the maximum base shear force of the platform in the absence of viscous dampers is 8.4058 N. Hence, it is clear that the maximum reduction of the base shear force is achieved with the toggle configuration. However, the base shear force associated with the toggle configuration has the lowest absolute value among all configurations and, therefore, this configuration is highly recommended for the lower level stories of the structure. For instance, by assuming a reference damping coefficient of 500 N.s/m, the maximum base shear force of chevron, toggle, and diagonal configurations are 8.24215 N, 7.89724 N, and 8.42302 N, respectively. The reason for this is related to the brace stiffness to dampers' damping coefficient ratio (K/C_D): an increase in K/C_D gives a reduction in the phase difference between the stories displacement and the axial displacement of the damper.

Table 6. The variations of the maximum base shear versus the variations of the damping coefficient for various configurations

Damping coefficient (N.s/m)	Maximum base shear (N)		
	Chevron configuration	Toggle configuration	Diagonal configuration
500	8.24215	7.89724	8.42302
1000	8.23423	7.89579	8.42101
1500	8.22936	7.89536	8.41813
2000	8.22648	7.89548	8.41271
2500	8.22491	7.89530	8.40762
3000	8.22420	7.89554	8.39785
3500	8.22405	7.89586	8.39459
4500	8.22427	7.89596	8.39059
4500	8.22472	7.89612	8.38768
5000	8.22531	7.89634	8.38914

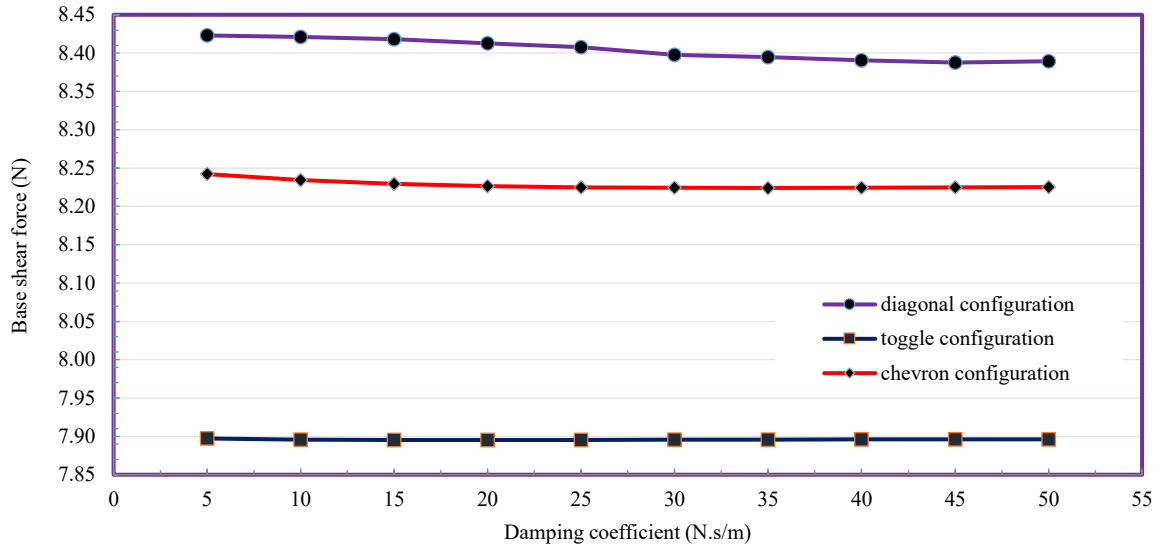


Fig. 19. The influence of the damping coefficient on the reduction of the base shear force

4.4. Optimizing the viscous dampers' performances using a non-uniform distribution

Ocean wave forces applied to submerged structures depend on the distance from the still water level (SWL). In other words, the structural elements that are located in deeper positions undergo a smaller wave forcing in comparison to the elements located near the SWL. Hence, it is logical to optimize the damper distribution throughout the height of the structure. To achieve the best-optimized spatial distribution for each configuration, it is essential to find the optimized damping coefficients. This is here studied by comparing the findings obtained with both uniform and non-uniform distributions of viscous dampers for the three different configurations of interest.

As summarized by Table 5, when the reference damping coefficient of all stories is 500 N.s/m and the brace area is 86.8 mm², the displacements of the deck are 0.11206 mm, 0.06458 mm, and 0.17790 mm for chevron, toggle, and diagonal configurations, respectively. This finding is in line with the results of Sections 4.2 and 4.3, showing that the toggle configuration outperforms other configurations with reference to deck displacement. Since the toggle configuration outperforms the chevron and diagonal configurations regarding the base shear and deck displacement, the results of the non-uniform distribution of viscous dampers at different stories are given for the case of toggle configuration. As indicated in Table 7, for all the cases the brace area is 86.8 mm². It is clear that an increase in the damping coefficient decreases deck displacement. Moreover, in most cases, the toggle configuration performs significantly better than the other configurations to reduce the deck displacements. However, the displacement of the platform in the absence of the damper is 0.071 mm. To understand the effects of non-uniform distribution on the dynamic response of the jacket platform, the results of the non-uniform distribution chevron configuration are summarized in

Table 7, where the first story is the ground floor. In order to find the optimized damping coefficient for the fourth story, the values of damping coefficient for the dampers of all other stories are kept constant and only the value of fourth story damping coefficient is changed in the range of from 4500 N.s/m down to 500 N.s/m. The results suggest that the minimum deck displacement occurs when the damping coefficient of the fourth story is 4500 N.s/m. Similarly, the optimized values of the damping coefficients for the other stories are given in Table 7. For small deck displacement differences, i.e. the percentage difference of two consecutive values smaller than 10%, the smaller damping coefficient is chosen to reduce the costs.

Table 7. The displacement of the platform deck for non-uniform distribution of the viscous damper in toggle configuration for a brace area of $86.8 \times 10^{-6} \text{ m}^2$

Desired story*	damping coefficient (N.S/m)				The standard deviation of deck displacement ($\times 10^{-3} \text{ m}$)
	Fourth story	Third story	Second story	First story	
Fourth story	4500	4500	4500	4500	0.04984
	4000	4500	4500	4500	0.05032
	3500	4500	4500	4500	0.05145
	3000	4500	4500	4500	0.05287
	2500	4500	4500	4500	0.05471
	2000	4500	4500	4500	0.05862
	1500	4500	4500	4500	0.05937
	1000	4500	4500	4500	0.07640
	500	4500	4500	4500	0.10413
Third story	4500	4000	4500	4500	0.05020
	4500	3500	4500	4500	0.05096
	4500	3000*	4500	4500	0.05129
	4500	2500	4500	4500	0.05226
	4500	2000	4500	4500	0.05410
	4500	1500	4500	4500	0.05441
	4500	1000	4500	4500	0.05927
	4500	500	4500	4500	0.08458
Second story	4500	3000	4000	4500	0.05132
	4500	3000	3500	4500	0.05138
	4500	3000	3000	4500	0.05146
	4500	3000	2500*	4500	0.05186
	4500	3000	2000	4500	0.05284
	4500	3000	1500	4500	0.05292
	4500	3000	1000	4500	0.05341
	4500	3000	500	4500	0.05951
First story	4500	3000	2500	4000	0.05189
	4500	3000	2500	3500	0.05190
	4500	3000	2500	3000	0.05192
	4500	3000	2500	2500*	0.05210
	4500	3000	2500	2000	0.05257
	4500	3000	2500	1500	0.05265
	4500	3000	2500	1000	0.05312
	4500	3000	2500	500	0.05440

*The story in where the optimal damping coefficient will be specified for it while the damping coefficients of the other stories are constant.

4.5. Application of the brace-viscous damper system to field jacket platforms

In this section, the efficiency of brace-viscous dampers system with various configurations and brace stiffness is investigated with reference to four offshore steel jacket platforms under real sea condition. The platforms are made up of tubular steel elements and they are regarded as a multi-degrees-of-freedom system to develop theoretical equations and numerical models

(Fig. 20). Patil and Jangid [19] studied the performance of viscoelastic, viscous and friction dampers installed at each floor under unidirectional random wave loading. The platforms have various structural properties and their depth of location are 121.92, 182.88, 243.84 and 304.8 m water depth for platform 1, 2, 3, and 4, respectively (for detailed information about the wave spectrum, platforms and dampers refer to [19]).

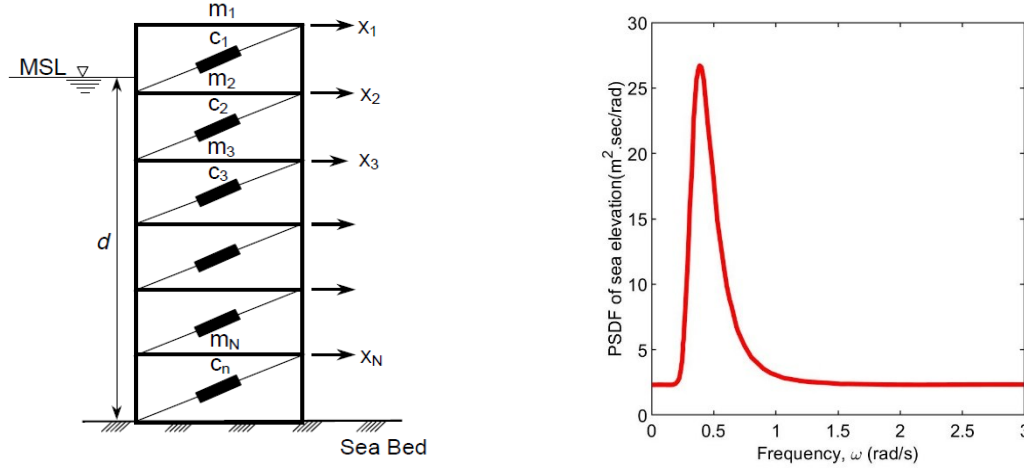


Fig. 20. The idealized form of field platforms of Patil and Jangid [19] (left panel); Pierson-Muskowitz wave spectrum (right panel)

As shown in Fig. 20, Patil and Jangid [19] investigated the effectiveness of diagonal viscous and viscoelastic dampers in the offshore jacket platforms using spectral analysis. The Pierson-Muskowitz spectrum for a uniform wind velocity equal to 22.86 m/s is used to produce the wave forces. In order to compare the effects of various viscous dampers' configurations (e.g. chevron and toggle) on the dynamic response of the considered platforms, the diagonal configuration is here substituted with chevron and toggle configurations. As suggested by Fig. 21, the toggle configuration with constant damping outperforms chevron, diagonal configurations and, obviously, the condition with no dampers. As proved in the previous sections, the toggle configuration performs better than the other configurations with reference to the dynamic response of offshore platforms. The results of Fig. 21 are completely in line with the previous findings. The effectiveness of the toggle configuration in mitigating the offshore jacket platform displacement is more evident when the platform is installed in deep waters. It is also worth to mention that the chevron configuration outperforms the diagonal configuration in terms of power spectral density function (PSDF) of top floor displacements.

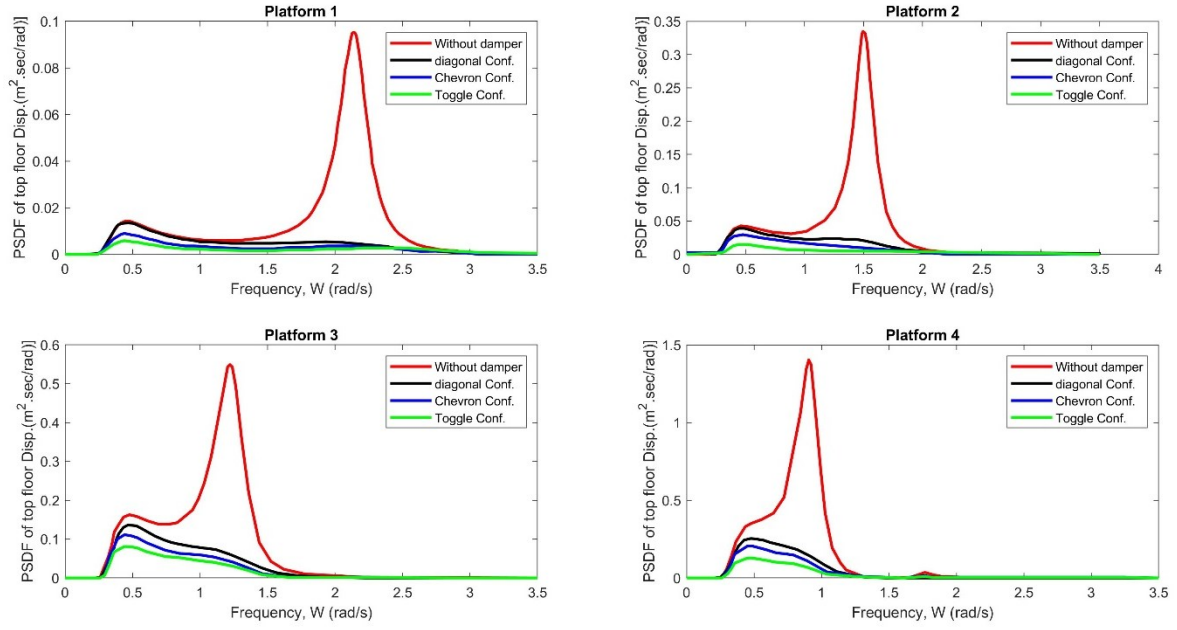


Fig. 21. Variation of top floor displacement against frequency for various platforms without and with various configurations of viscous dampers

*PSDF= power spectral density function

The performance of the toggle configuration is compared with that of both viscoelastic damper and uncontrolled platform in terms of standard deviation of the top floor displacements. Patil and Jangid [19] investigated the effects of various dampers arrangements on the top floor displacement of the platforms. They proved that use of diagonal and viscoelastic dampers, controlling the platform, can significantly mitigate the dynamic response of the structure. Furthermore, they proved that the viscoelastic damper outperforms the diagonal viscous damper with reference to top floor displacements. However, they did not compare the performance of viscoelastic, toggle and chevron dampers. Since the toggle configuration proved to be better than the chevron in the mitigation of platform displacements, we compared the displacements reduction associated with both viscoelastic and toggle dampers. As summarized in Table 8, the most economical and optimal arrangement for platform number 1 is the 5th case for both the viscoelastic and toggle viscous dampers. However, the reduction percentage associated with the toggle viscous damper (for the first platform, 43.06%) is larger than that of the viscoelastic damper (for the first platform, 32.27%). A similar trend exists for other platforms but as the installation depth of the platforms increases, the difference between the reduction percentage of viscoelastic and toggle viscous dampers decreases.

Table 8. Comparison of the standard deviation of top floor displacements of the platforms for different arrangements of the dampers

Platform NO.	Case	Damper arrangement at floors	The standard deviation of top floor displacements ($\times 10^{-3}$ m)			Reduction percentage of top floor displacements by viscoelastic damper	Reduction percentage of top floor displacements by viscous damper with toggle configuration
			Uncontrolled	viscoelastic damper	viscous damper with toggle configuration		
1	1	All floors	0.2127	0.1245	0.1009	41.46	52.56
	2	1, 2, 6, 7	0.2127	0.1543	0.1237	27.47	41.84
	3	1, 2, 4, 6	0.2127	0.1449	0.1202	31.89	43.49
	4	2, 4, 6, 7	0.2127	0.1565	0.1271	26.41	40.24
	5	1, 3, 4, 6	0.2127	0.1441	0.1211	32.27	43.06
	6	1, 2, 3, 6	0.2127	0.1444	0.1221	32.09	42.59
2	1	All floors	0.3556	0.1921	0.1692	45.07	52.42
	2	1, 2, 3, 4	0.3556	0.2391	0.2101	32.75	40.91
	3	1, 2, 4, 6	0.3556	0.2242	0.2007	36.95	43.56
	4	1, 3, 4, 6	0.3556	0.2241	0.2007	36.96	43.56
	5	1, 2, 3, 6	0.3556	0.2515	0.2298	29.27	35.37
	6	1, 2, 4, 7	0.3556	0.2468	0.2217	30.58	37.65
	7	1, 2, 5, 7	0.3556	0.2548	0.2311	28.35	35.01
	8	1, 2, 5, 6	0.3556	0.2325	0.2076	34.61	41.62
3	1	All floors	0.5170	0.2839	0.2543	45.08	50.81
	2	1, 2, 3, 4	0.5170	0.3387	0.3104	34.50	39.96
	3	1, 2, 4, 6	0.5170	0.3422	0.3142	33.82	39.22
	4	1, 3, 4, 6	0.5170	0.3146	0.2876	39.16	44.37
	5	1, 2, 3, 6	0.5170	0.3618	0.3352	30.01	35.16
	6	1, 2, 4, 7	0.5170	0.3727	0.3437	27.92	33.52
	7	1, 3, 5, 6	0.5170	0.3475	0.3151	32.79	39.05
	8	1, 3, 6, 7	0.5170	0.3697	0.3367	28.49	34.87
4	1	All floors	0.6815	0.3212	0.3002	52.87	55.95
	2	1, 2, 3, 4	0.6815	0.4835	0.4691	29.06	31.16
	3	1, 2, 4, 6	0.6815	0.4634	0.4481	32.00	34.24
	4	1, 3, 4, 6	0.6815	0.4131	0.3817	39.38	44.00
	5	1, 2, 3, 6	0.6815	0.4839	0.4697	28.99	31.07
	6	1, 2, 5, 6	0.6815	0.4570	0.4237	32.94	37.82
	7	1, 3, 5, 6	0.6815	0.4212	0.3991	38.19	41.43
	8	1, 3, 6, 7	0.6815	0.4679	0.4484	31.34	34.20

5. Summary and conclusions

The effects of various distributions and configurations of viscous dampers as well as brace stiffness along the height of an offshore jacket platform have been studied by numerical simulations carried out using the ANSYS software package. The model four-legged jacket of Elshafey et al. [23], implementing a combination of brace-viscous damper system has been used for the analysis. The irregular wave forcing has been reproduced by means of the JONSWAP spectrum.

The simulation results have been verified by comparing with Elshafey et al. [23], including the results of the 1st-10th vibration frequencies and jacket free vibration. A benchmarking of the viscous damper performances has also been made by comparing the response of the simulated viscous damper with that of the experimental model proposed by Ou et al. [14]. The experimental results of Soong and Dargush [36], Rama Raju et al. [37], and

Constantinou and Symans [33] are exploited for the validation of viscous damper simulations with toggle, chevron and toggle configurations, respectively. The comparison between our numerical results with those of Tabeshpour and Janbazi Rokni [24] revealed the accuracy of our numerical simulations regarding the controlling effects of diagonal brace-viscous damper systems installed on a field jacket platform. Both checks indicate that jacket and viscous damper simulations can suitably reproduce the reference experimental results.

Subsequently, the influence of the brace area on the performance of the viscous damper has been investigated. Using constant values of the damping coefficient, the results suggest that an increase in the brace area leads to a reduction of the platform displacement. In other words, the reduction in the structure displacement with an increase in the brace area for chevron configuration is more than that of the diagonal and toggle configurations. This is due to the brace stiffness, which is directly proportional to the brace area.

Then, the impact of the damper configuration, including diagonal, chevron, and toggle configurations, has been analyzed with reference to the base shear force. To achieve this goal, the damping coefficient of the viscous damper for all the three configurations has been changed. The optimum base shear forces for diagonal, chevron and toggle configurations have been found to be 8.39, 8.23, and 7.89 N, respectively.

It has been shown that the toggle configuration can produce larger forces associated with small damping coefficients. Hence, this specific configuration is very efficient for the stories adjacent to the base of the structure. The results indicate that the toggle configuration has mitigated both the base shear force and the platform displacement more than those of the other configurations.

Accordingly, the distribution of chevron damper in various stories of the structure has been analyzed to define the best-optimized architecture for the dampers. The results show that using non-uniform distributions can lead to economic designs. With different damping coefficients, equal to 4500, 3500, 2500, and 2500 N.s/m for the fourth, third, second and first stories, respectively, the standard deviation of displacements of the deck (fourth story) is 0.0521 mm. However, with a constant damping coefficient (4500 N.s/m) for all the stories, the displacement of the deck is 0.04984 mm, and the difference is not significant. Hence, using an optimum design for both dampers and braces leads to a significant reduction in expenses, while their performances are the same. Moreover, our results show that it is highly recommended to use the non-uniform distribution of toggle configuration for the seeking of optimization.

To evaluate the efficiency of the optimal configuration (toggle configuration), its capability in mitigating the dynamic response is also evaluated with reference to the large scale measurements of Patil and Jangid [19]. To do this, four offshore steel jacket platforms under real sea condition are investigated in (1) uncontrolled condition; (2) with viscoelastic damper; (3) with viscous damper with toggle configuration. The results proved that the application of dampers can significantly mitigate the top floor displacements. Further, it is shown that the toggle viscous damper outperforms the viscoelastic dampers with reference to the top floor displacement and displacement reduction rate (with respect to uncontrolled condition). For instance, in the case of the first platform the reduction rate of the top floor displacement associated with viscoelastic and toggle viscous dampers are 32.27% and 43.06%, respectively. However, it proved that the difference in the reduction rate of the top floor displacement of viscoelastic and toggle viscous dampers reduces when the platform is in deep waters, e.g. for the first platform (located at depth 121.92m) the difference is 33% and for the second platform (located at depth 182.88m) the difference is 18%.

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References

- [1] M. Vaezi, A. Pourzangbar, M. Fadavi, A. Rahbar Rangi, Configuration effects on the performance of viscous dampers (Text in Persian), in: 4th International Congress on Civil Engineering, Architecture, and Urban Development, Shahid Beheshti University, Tehran, Iran, 2016.
- [2] Y.T. Chen, Y.H. Chai, Effects of brace stiffness on performance of structures with supplemental Maxwell model-based brace-damper systems, *Earthq. Eng. Struct. Dyn.* (2011). <https://doi.org/10.1002/eqe.1023>.
- [3] B.L. Zhang, Q.L. Han, X.M. Zhang, Recent advances in vibration control of offshore platforms, *Nonlinear Dyn.* (2017). <https://doi.org/10.1007/s11071-017-3503-4>.
- [4] X. Tang, L. Zuo, Simulation and experiment validation of simultaneous vibration control and energy harvesting from buildings using tuned mass dampers, in: *Proc. Am. Control Conf. San Fr. CA, USA*, 2011: pp. 3134–3139.
- [5] J. Zhang, Z. Ma, F. Liu, C. Zhang, P. Sharafi, M. Rashidi, Seismic Performance and Ice-Induced Vibration Control of Offshore Platform Structures Based on the ISO-PFD-SMA Brace System, *Adv. Mater. Sci. Eng.* (2017). <https://doi.org/10.1155/2017/3596094>.
- [6] S. Huang, M. Cai, Z. Xiang, Robust sampled-data H_∞ control for offshore platforms subject to irregular wave forces and actuator saturation, *Nonlinear Dyn.* (2017). <https://doi.org/10.1007/s11071-017-3404-6>.
- [7] R. Kandasamy, F. Cui, N. Townsend, C.C. Foo, J. Guo, A. Sheno, Y. Xiong, A review of vibration control methods for marine offshore structures, *Ocean Eng.* (2016). <https://doi.org/10.1016/j.oceaneng.2016.10.001>.
- [8] C. Zhang, J. Ou, Control structure interaction of electromagnetic mass damper system for structural vibration control, *J. Eng. Mech.* (2008). [https://doi.org/10.1061/\(ASCE\)0733-9399\(2008\)134:5\(428\)](https://doi.org/10.1061/(ASCE)0733-9399(2008)134:5(428)).
- [9] W. Wang, X. Hua, X. Wang, J. Wu, H. Sun, G. Song, Mechanical behavior of magnetorheological dampers after long-term operation in a cable vibration control system, *Struct. Control Heal. Monit.* (2019). <https://doi.org/10.1002/stc.2280>.
- [10] M.H. Stanikzai, S. Elias, V.A. Matsagar, A.K. Jain, Seismic response control of base-isolated buildings using tuned mass damper, *Aust. J. Struct. Eng.* 00 (2019) 1–12. <https://doi.org/10.1080/13287982.2019.1635307>.
- [11] X. Yin, G. Song, Y. Liu, Vibration suppression of wind/traffic/bridge coupled system using multiple pounding tuned mass dampers (MPTMD), *Sensors (Switzerland)*. (2019). <https://doi.org/10.3390/s19051133>.
- [12] A. Pourzangbar, M. Vaezi, seyed M. Mousavi, A. Saber, Analysis of damper configuration and brace stiffness effects on the performance of brace-viscous damper systems in steel frames, *Int. J. Eng. Basics, Appl. Asp.* (2020). <https://dx.doi.org/10.5829/ije.2020.33.05b.02>.
- [13] J. Ou, X. Long, Q.S. Li, Y.Q. Xiao, Vibration control of steel jacket offshore platform structures with damping isolation systems, *Eng. Struct.* (2007). <https://doi.org/10.1016/j.engstruct.2006.08.026>.

- [14] J.P. Ou, X. Long, Q.S. Li, Seismic response analysis of structures with velocity-dependent dampers, *J. Constr. Steel Res.* (2007). <https://doi.org/10.1016/j.jcsr.2006.06.034>.
- [15] W. Lin, Y. Lin, G. Song, J. Li, Multiple Pounding Tuned Mass Damper (MPTMD) control on benchmark tower subjected to earthquake excitations, *Earthq. Struct.* (2016). <https://doi.org/10.12989/eas.2016.11.6.1123>.
- [16] M.D. Symans, F.A. Charney, A.S. Whittaker, M.C. Constantinou, C.A. Kircher, M.W. Johnson, R.J. McNamara, Energy dissipation systems for seismic applications: Current practice and recent developments, *J. Struct. Eng.* (2008). [https://doi.org/10.1061/\(ASCE\)0733-9445\(2008\)134:1\(3\)](https://doi.org/10.1061/(ASCE)0733-9445(2008)134:1(3)).
- [17] S. Paul, T.K. Datta, S. Kapuria, Control of fixed offshore jacket platform using semi-active hydraulic damper, *J. Offshore Mech. Arct. Eng.* (2009). <https://doi.org/10.1115/1.3160534>.
- [18] H.H. Lee, S.H. Wong, R.S. Lee, Response mitigation on the offshore floating platform system with tuned liquid column damper, *Ocean Eng.* (2006). <https://doi.org/10.1016/j.oceaneng.2005.06.008>.
- [19] K.C. Patil, R.S. Jangid, Passive control of offshore jacket platforms, *Ocean Eng.* (2005). <https://doi.org/10.1016/j.oceaneng.2005.01.002>.
- [20] M.C. Constantinou, P. Tsopelas, W. Hammel, A.N. Sigaher, Toggle-brace-damper seismic energy dissipations systems, *J. Struct. Eng. New York, N.Y.* (2001). [https://doi.org/10.1061/\(ASCE\)0733-9445\(2001\)127:2\(105\)](https://doi.org/10.1061/(ASCE)0733-9445(2001)127:2(105)).
- [21] R. Zhang, H. He, D. Weng, H. Zhou, S. Ding, Theoretical analysis and experimental research on toggle-brace-damper system considering different installation modes, *Sci. Iran.* (2012). <https://doi.org/10.1016/j.scient.2012.10.011>.
- [22] P. Dou, M.A. Xue, J. Zheng, C. Zhang, L. Qian, Numerical and experimental study of tuned liquid damper effects on suppressing nonlinear vibration of elastic supporting structural platform, *Nonlinear Dyn.* (2020). <https://doi.org/10.1007/s11071-019-05447-y>.
- [23] A.A. Elshafey, M.R. Haddara, H. Marzouk, Dynamic response of offshore jacket structures under random loads, *Mar. Struct.* (2009). <https://doi.org/10.1016/j.marstruc.2009.01.001>.
- [24] M.R. Tabeshpour, H.J. Rokni, Frequency Domain Long-Term Efficiency of Viscous Damper in Jacket Platforms Under Random Wave Load, *Arab. J. Sci. Eng.* (2017). <https://doi.org/10.1007/s13369-017-2534-y>.
- [25] H. Janbazi Rokni, M.R. Tabeshpour, Spectral fatigue analysis of jacket platform under wave load equipped with viscous damper, *J. Mar. Sci. Technol.* (2018). <https://doi.org/10.1007/s00773-018-0592-9>.
- [26] H. Hokmabady, S. Mohammadyzadeh, A. Mojtahedi, Suppressing structural vibration of a jacket-type platform employing a novel Magneto-Rheological Tuned Liquid Column Gas Damper (MR-TLCGD), *Ocean Eng.* (2019). <https://doi.org/10.1016/j.oceaneng.2019.03.055>.
- [27] M.H. Enferadi, M.R. Ghasemi, N. Shabakhty, Wave-induced vibration control of offshore jacket platforms through SMA dampers, *Appl. Ocean Res.* (2019). <https://doi.org/10.1016/j.apor.2019.06.005>.

- [28] S.A. Arjmandi, M. Heidari, Vibration control of jacket offshore platforms subjected to irregular wave loads using damping isolation system, *Sci. J. Manag. Syst.* 5 (2019) 83–100. http://ijmt.iranjournals.ir/article_32554.html.
- [29] C. Zhou, Z. Gao, Y. Chen, T. Zhang, S. A, Seismic Control Analysis of Railway Bridge Strengthened with Viscous Dampers [增设黏滞阻尼器加固铁路桥梁的减震控制分析], *J. Railw. Eng. Soc.* 36 (2019) 54–58 and 85.
- [30] B.-B. Chen, Z.-R. Feng, X.-J. Wang, Analysis of Damping Effect of Cable-Stayed Bridges Installed with Viscous Dampers Under Long Period Ground Motion [长周期地震动作用下斜拉桥粘滞阻尼器减震分析], *Bridg. Constr.* 48 (2018) 75–80.
- [31] Y.H. Sun, Q. Niu, L.W. Nie, J.G. Zhang, Vibration control of offshore platform based on outrigger damping system, *Appl. Mech. Mater.* 351–352 (2013) 1112–1116. <https://doi.org/10.4028/www.scientific.net/AMM.351-352.1112>.
- [32] D. Lee, D.P. Taylor, Viscous damper development and future trends, *Struct. Des. Tall Build.* (2001). <https://doi.org/10.1002/tal.188>.
- [33] M.C. Constantinou, M.D. Symans, Experimental and analytical investigation of seismic response of structures with supplemental fluid viscous dampers, Buffalo; NY, 1992.
- [34] A.K. Agrawal, M. Amjadian, Seismic component devices, in: *Innov. Bridg. Des. Handb. Constr. Rehabil. Maint.*, 2015. <https://doi.org/10.1016/B978-0-12-800058-8.00020-7>.
- [35] J.S. Hwang, Y.N. Huang, Y.H. Hung, Analytical and experimental study of toggle-brace-damper systems, *J. Struct. Eng.* (2005). [https://doi.org/10.1061/\(ASCE\)0733-9445\(2005\)131:7\(1035\)](https://doi.org/10.1061/(ASCE)0733-9445(2005)131:7(1035)).
- [36] T.T. Soong, G.F. Dargush, *Passive Energy Dissipation Systems in Structural Engineering*, John Wiley and Sons Ltd, n.d. <https://www.wiley.com/en-it/Passive+Energy+Dissipation+Systems+in+Structural+Engineering-p-9780471968214>.
- [37] K. Rama Raju, M. Ansu, N.R. Iyer, A methodology of design for seismic performance enhancement of buildings using viscous fluid dampers, *Struct. Control Heal. Monit.* 21 (2014) 342–355. <https://doi.org/10.1002/stc.1568>.