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PERFORMANCE OF STEEL PLATE REINFORCED CONCRETE COMPOSITE SHEAR WALLS UNDER STATIC AND HARMONIC LOADINGS- SMART SOLUTION

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Abstract

Smart solutions for structural members to increase the strength capacity and reduce the deformations has applied in recent years. The presence of straight steel plate that connected by steel columns inside the reinforced concrete shear wall giving high strength resistance against static and dynamic loadings due to super elasticity and shape memory effect of materials. The present paper focus on the performance of composite shear wall under the effects of static and dynamic harmonic loadings with different frequencies. Different parameters considered, such as the frequency range, compressive strength of concrete and loading type. The analysis results indicated that the super elastic of adopted material as steel plate and columns that embedded inside the shear wall has more significant effects on the shear wall that subjected to static and dynamic loading and decrease the deflection and stress concentrations of the composite shear wall system. The dynamic harmonic analysis shows that the displacements increased at a specific frequency that represents the critical frequency that caused maximum displacement. The reduction in displacements varies between 35 to 99% due to an increase in compressive strength and presences of steel columns and steel plate as a smart solution.

Keywords: Composite structure, Dynamic response, Harmonic loadings, Shear wall, Smart material.

1. Introduction

Shear wall is the structural element that mainly resists lateral forces such as wind and seismic loadings especially in tall buildings. The stud shear connectors welded at both sides of plate and steel columns webs. Cast in situ concrete inside the mould that contained the steel plate and steel columns so that with sufficient shear stud connectors working as unity in additions to vertical and horizontal reinforcements.

The differential equation that derived from Newton second law consists of three components as acceleration, velocity, and displacement. This basic equation coupled with a harmonic force so that it defines the relationship between applied harmonic force and displacement. The composite shear walls under the effects of harmonic loadings especially in roadways infrastructures or conventional railways is significant for stabilize earth. The conventional shear wall has lower ductility, and deformability [1].

Composite shear wall gave strength and high stiffness with high deformable due to presences of the steel plate and steel columns [2]. Increase the shear stud connectors in composite wall increase the ductility of the composite wall, and the slope of the load-displacement become less [2]. The behaviour of composite walls under the effects of cyclic loadings showed that good ductility and lateral resistance, the energy observations were increase with deflection [3, 4].

The magnitude of amplitude dynamic harmonic force and the same static applied force that applied on a shear wall not equivalent so that the principle of the equivalent level of energy must be consider and apply [5]. Different approaches such as stochastic harmonic function was adapted to analyse shear wall under the effect of harmonic loadings. This approach gave good results as compared with the classical method [6].

In present paper and based on the previous studied, the impact of harmonic loadings on composite shear wall try to fill the gap in this field and open a lot of ideas for future works.

2. Objectives and Scope of the study

The performance of the gravity static and harmonic loadings of the composite shear walls are analyse using finite the element approach. Different parameters are considered in the analysis, such as the frequency range and compressive strength of concrete and type of loadings such as static and harmonic. The numerical analysis as explicit by ANSYS software and the deformations, stresses and dynamic response discussed.

3. Harmonic Analysis

Harmonic analyses of the structural system that adopted in the present study to determine the steady-state response of a linear reinforced concrete and composite shear wall under the effects of harmonic loads. The dynamic analysis was considered to verify whether the shear walls (concrete and composite) designs will successfully overcome resonance and other damage of forced vibrations.

The domain analysis relies on the applied varying loads that represent the main parameter that influenced the structural system under the effect of dynamic loading. Based on Newton second law of motion, the applied load changing with time or frequency with sine amplitude load as cosine or sine wave as follow [7]:

$$R(t) = P_0 \cos(\omega t) + P_{90} \sin(\omega t) \quad (1)$$

The applied loading in eq. (1) exists for any time in which the steady-state conditions have been reaching or attain. The spatial loading includes the in-phase component P_0, and the P_{90} rotate by 90° out-of-phase component. The spatial distributions do not vary as a function of time. The equilibrium equation for the structural system is Eq. (2):

$$m u''(t) + c u'(t) + k u(t) = P_0 \cos(\omega t) + P_{90} \sin(\omega t) \quad (2)$$

The complex expression of eq. (1) as follows:

$$\bar{R}(t) = \bar{P} e^{i\omega t} = \bar{P}[\cos(\omega t) + i \sin(\omega t)] \quad (3)$$

The steady-state solution of equation (3) in term of node displacements as follows:

$$[k + i\omega c - \omega^2 m]\bar{a} = \bar{P} \quad (4)$$

In which the complex matrix as follows:

$$\bar{k}(\omega)\bar{a}(\omega) = \bar{P}(\omega) \quad (5)$$

In the present analysis, the frequency domain instead of the time domain so that the equation become a damping matrix in the form of as follow:

$$D = \omega c \quad (6)$$

Hysteretic damping specified as a function of frequency ($D = D(\omega)$) so that the complex impedance matrix become as:

$$\bar{k}(\omega) = k(\omega) - \omega^2 m + i D(\omega) \quad (7)$$

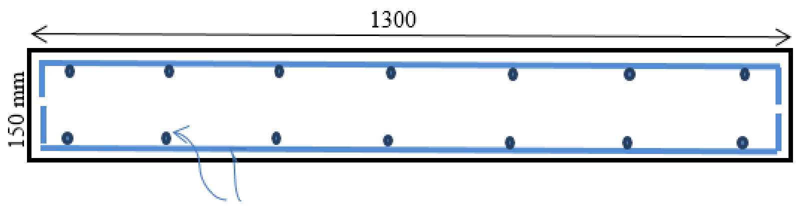
The frequency domains analyses that adopt in the present model analysis are perform at discrete frequency steps.

4. Model Descriptions

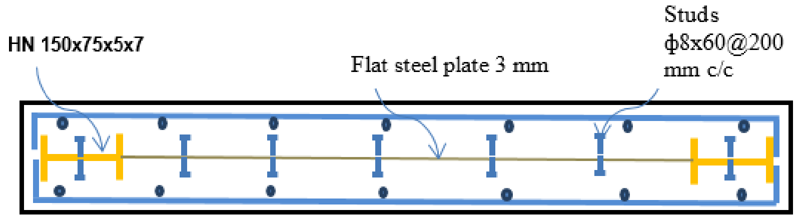
Shear walls model divided into a reinforced and a composite shear wall that shown in Fig. 1 and lists in Table1. Shear wall models (1750 mm height), width (1300 mm) and thickness of (150 mm) that adopted from the experimental test by Wang et al. [8].

Mechanical properties of the steel materials sections and their dimensions are lists in Tables 2 and 3. In reinforced concrete shear wall (RCSW) the vertical and horizontal reinforcements are ɸ6 mm @ 200 mm centre to centre in both directions.

In case of composite shear wall, same dimensions of RCSW but reinforced by two steel columns HN150x75x5x7 that connected by steel plate with (3 mm) in thickness. Stud shear connectors are provided with height to diameter ratio (7.5) in which the stud diameter (8 mm) and total height is (60 mm) distribute vertically at (200 mm) centre to centre. All details shown in Fig. 1 and Table 4 lists the model's descriptions.



(a) Vertical and horizontal reinforcement ϕ6@200 mm c/c



(b) Composite shear wall (CSW) [8]

Fig. 1. (a) Reinforced concrete shear wall (RCSW) and (b) Composite shear wall (CSW) [8].

Table 1. Shear stud connectors, reinforcement's distributions, and steel plate.

Shear stud connector	Main reinforcements	Steel plate thickness
diameter (8 mm) and total height is (60 mm) distribute vertically at (200 mm)	vertical and horizontal reinforcements are ϕ6mm@ 200 mm centre to centre in both directions	(3 mm) in thickness

Table 2. Mechanical properties of the steel plate and the steel column.

Steel section	Yield strength, f_y (MPa)	Ultimate strength f_u (MPa)	Modulus of elasticity E_s (GPa)	Poisson's ratio (ν)
Steel plate	281.37	399.59	206	0.30
Column - Flange	296.96	399.52	220	0.30
Column - Web	292.65	414.08	221	0.30

Table 3. Reinforced concrete wall and steel plate and column dimensions.

Reinforced concrete wall				
Height (mm)	**Thickness (mm)**	**Length (mm)**		
1750	150	1300		
Steel column				
Steel plate thickness (mm)	**Flange width (mm)**	**Flange thickness (mm)**	**Web height (mm)**	**Web thickness (mm)**
3	75	7	140	5

Table 4. Description of the models.

Model mark	Compressive strength (MPa)	Load type	Frequency range (Hz)	Frequency step (Hz)
RCSW30-S	30	Static	---	---
RCSW70-S	70	Static	---	---
CSW30-S	30	Static	---	---
CSW70-S	70	Static	---	---
RCSW30-H	30	Harmonic	0-40	2
RCSW70-H	70	Harmonic	0-40	2
CSW30-H	30	Harmonic	0-40	2
CSW70-H	70	Harmonic	0-40	2

Concrete compressive strength with grade C35 and C70 (cube compressive strength) with a modulus of elasticity is (25500 and 42650 MPa) and Poisson's ratio (0.15). Density for concrete and steel is (24000 and 7850 kg.m^3), respectively.

5. Supports and Loading conditions

All models of the shear walls are fixed from the bottom and free from the top. The load was applied at the upper midpoint of the model that represents the gravity load. The applied vertical load for all models was (650 kN). In the case of harmonic load, the static amplitude force remains constant, but the frequency range will change. The frequency range applied (0-40 Hz) with (2 Hz) as the frequency step for each applied load and all stresses and deformations result plotted with time (frequency).

6. Finite Element Method

ANSYS software [9] was used to analyse all shear wall models. Different elements are select that represent the actual behaviour of concrete, steel plate, steel columns, reinforcements, and the plate under the effect of applied gravity loads. SOLID65 element is for concrete due to its properties as crush and cracks, SOLID185 for steel plate and steel columns, LINK180 for vertical and horizontal reinforcements and SOLID186 for plates under the loads. The contact between two different materials such as concrete, steel plate and columns represent by CONTACT173 and TARGET170. The Newton - Raphson numerical method for the solution of the static load was apply in which displacement control with tolerance (0.001) adopted for static loading in which the applied load divided with steps of (250). In the case of harmonic loadings, the sparse method for dynamic explicit analysis was use. The typical composite wall shown in Fig. 2 present the model meshes for RCSW shows the vertical and horizontal reinforcements.

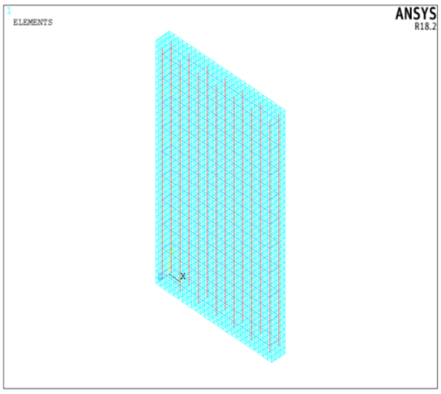


Fig. 2. Finite element model - reinforced concrete shear wall.

The finite elements simulation of CSW is show in Fig. 3 in which represents the full model, steel columns with steel plate and reinforcements.

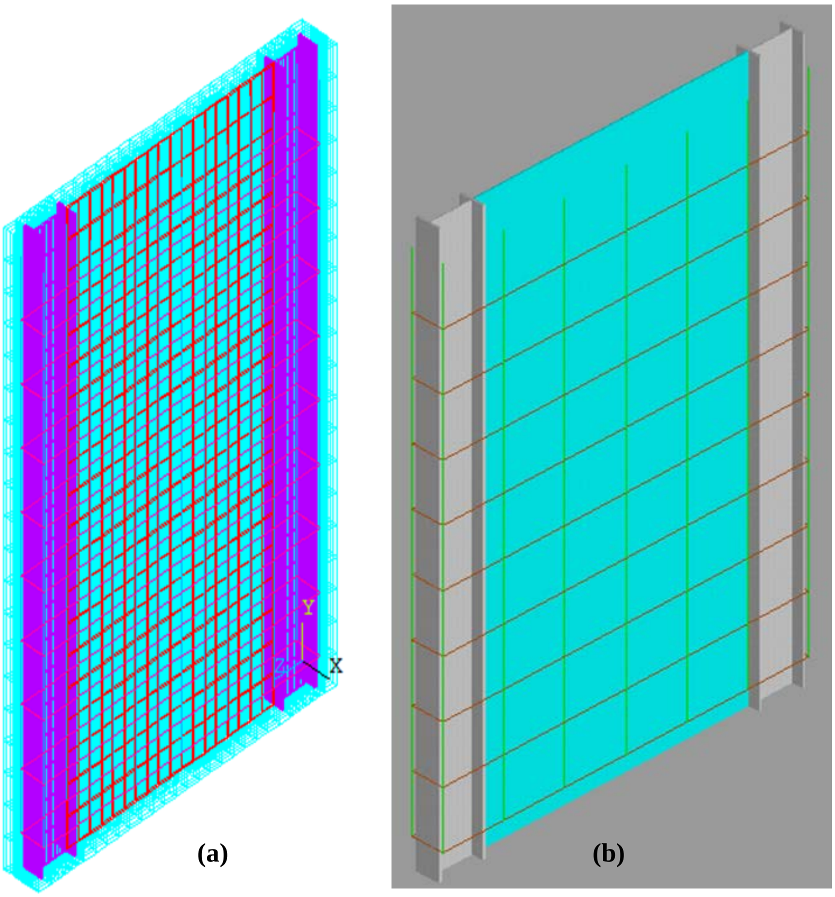


Fig. 3. Concrete sheer wall model (a) Full model and (b) Steel columns with steel plate and reinforcements.

7. Analysis Results

Analysis results for all models are presents as below. The loads have a significant incidence on the structural performance of reinforced concrete wall in cases of RCSW and CSW. Table 5 lists the results summary for all models under the effects of static and harmonic loadings. In the case of static load, the displacements in all wall directions as width, height, and thickness of RCSW and CSW are lists. The displacements of RCSW are higher than that CSW due to the composite action of the steel and concrete that lead to an increase in stiffness (moment of inertia and modulus of elasticity). The performances of the RCSW and CSW under harmonic loadings indicated that the increase in compressive concrete strength and the composite structures for full interaction gave more resistance than the RCSW against deformations.

Table 5. Descriptions of the models (Absolute values).

Model mark	Max dis-placement along the width (mm)	Max dis-placement along height (mm)	Max dis-placement along thickness (mm)	Freq (Hz)	% Decrease in Maximum dis-placement along height
RCSW30-S	0.0167	0.3468	0.0023	---	---
RCSW70-S	0.00987	0.2016	0.00129	---	41.87
CSW30-S	0.0164	0.2754	0.0021	---	20.59
CSW70-S	0.00996	0.177	0.00147	---	48.96
RCSW30-H	1.305	2.378	0.5761	34	---
RCSW70-H	0.003	0.0045	0.00146	Results for 34	---
CSW30-H	0.494	0.7465	0.412	18	---
CSW70-H	0.0476	0.109	0.126	Results for 18	---

Figure 4 shows the displacements along with the shear wall height in case of RCSW30 (compressive strength n30 MPa) that the displacements become higher near the applied load at the top area of the model and become zero at the bottom due to the location of the fixed support. Figure 5 presents the displacements along with the shear wall height in case of RCSW30 (compressive strength n30 MPa) that the displacements become higher near the applied load at the top area of the model and become zero at the bottom due to the location of the fixed support. Figure 5 also presents the longitudinal displacements of the CSW in which the maximum displacements less than that for RCSW30. Figures 6 and 7 show the longitudinal displacement of CSW30 and CSW70 that gave displacements less than for both RCSW30 and RCSW70 due to the increase in the compressive strength of the concrete wall.

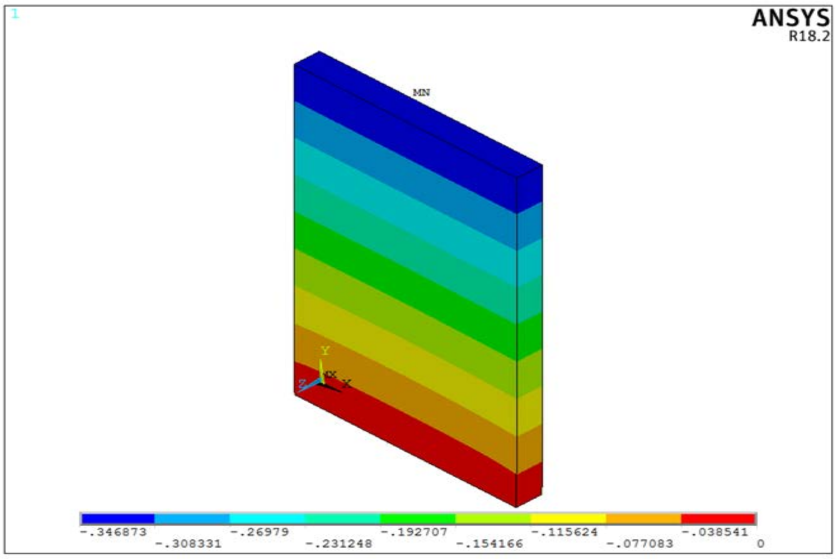


Fig. 4. Longitudinal displacement - RCSW30-S.

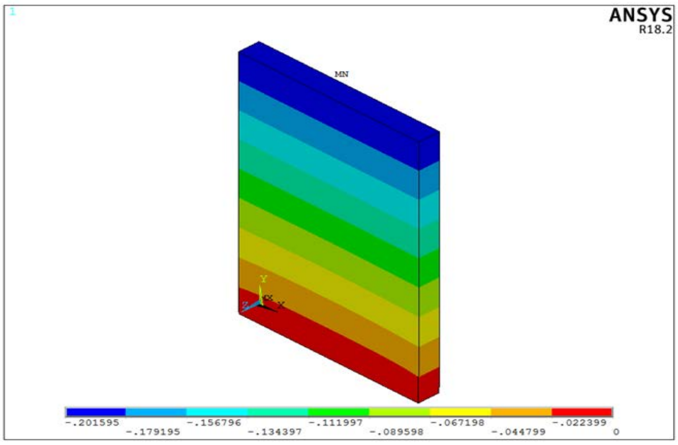


Fig. 5. Longitudinal displacement - RCSW70-S.

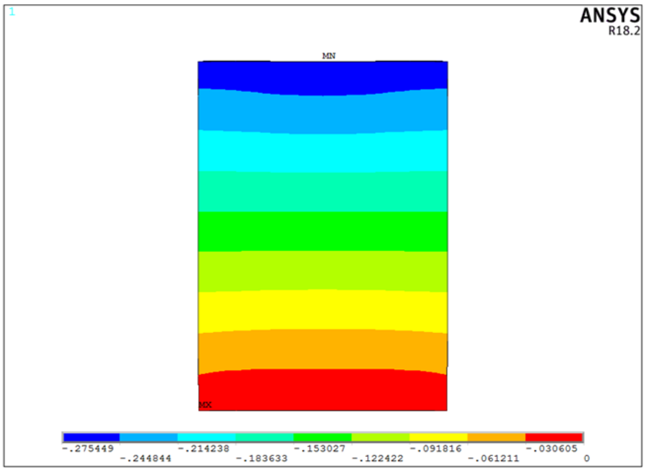


Fig. 6. Longitudinal displacement - CSW30-S.

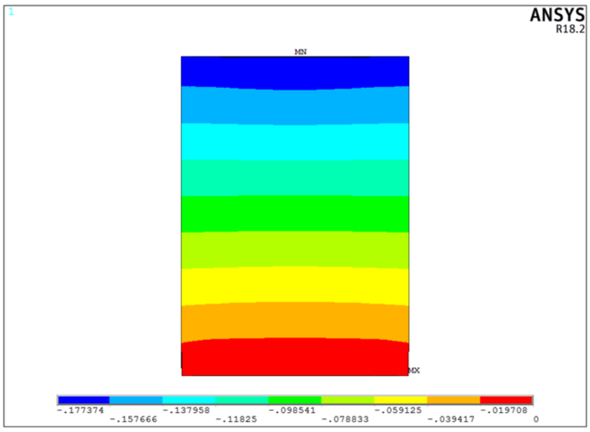


Fig. 7. Longitudinal displacement - CSW70-S.

Figures 8 to 19 represent the full performances and comparisons between the RCSW and CSW for the parameters considered in the study. Increase in compressive strength leads to reduce the displacements for the same frequency that lists in Table 6.

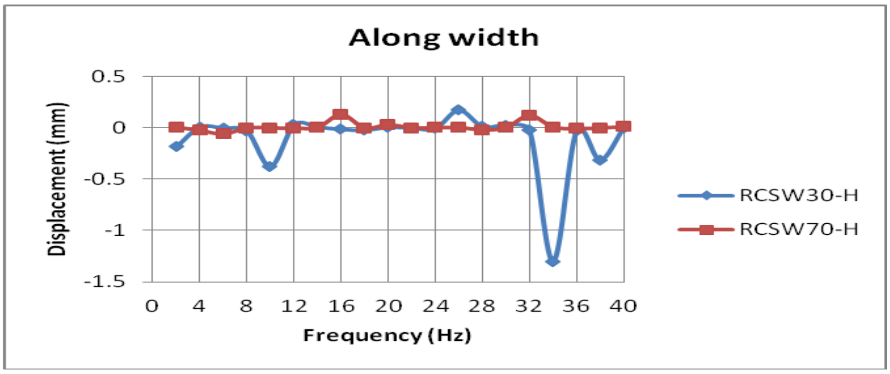


Fig. 8. Displacement frequency performance.

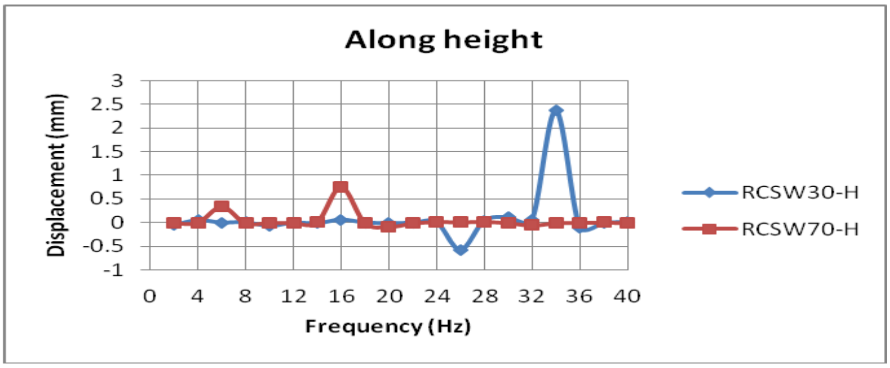


Fig. 9. Displacement frequency performance.

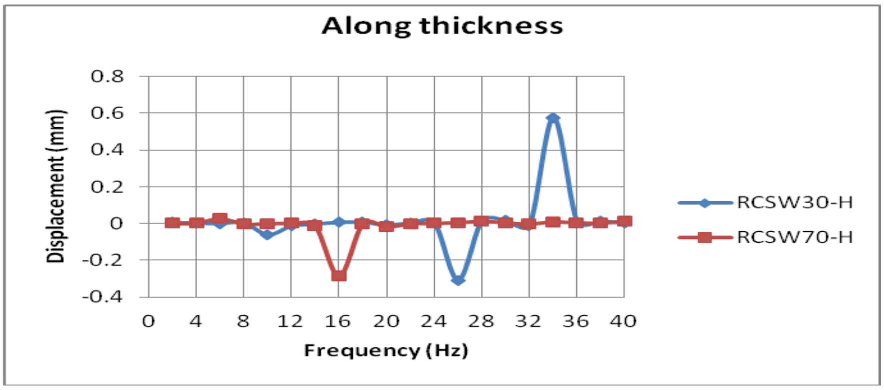


Fig. 10. Displacement frequency performance.

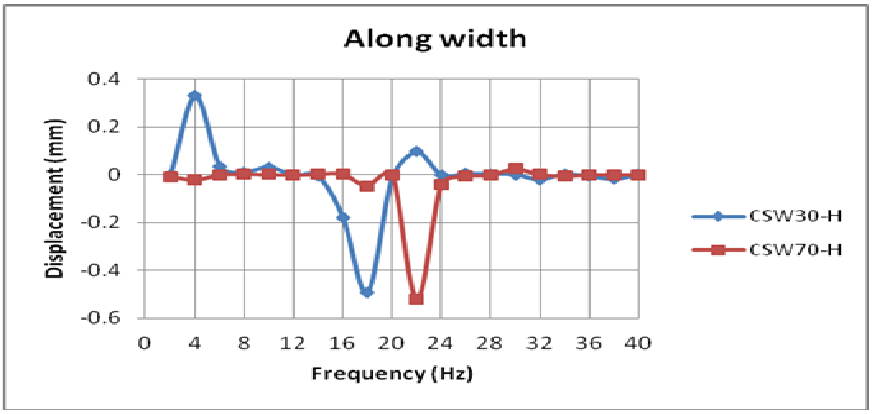


Fig. 11. Displacement frequency performance.

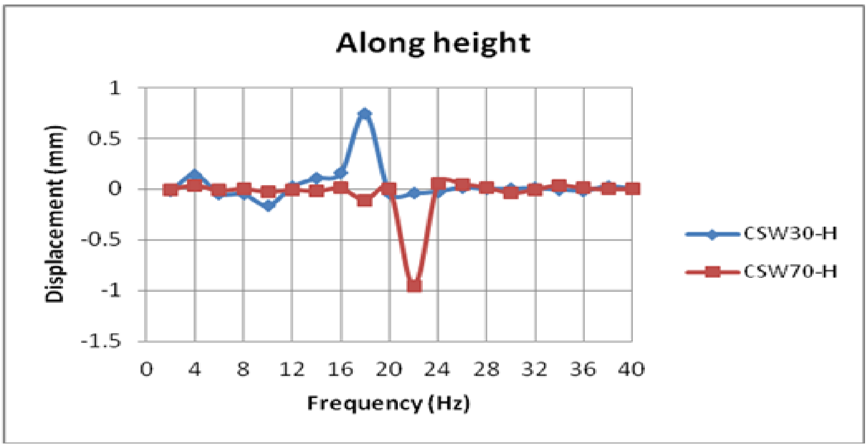


Fig. 12. Displacement frequency performance.

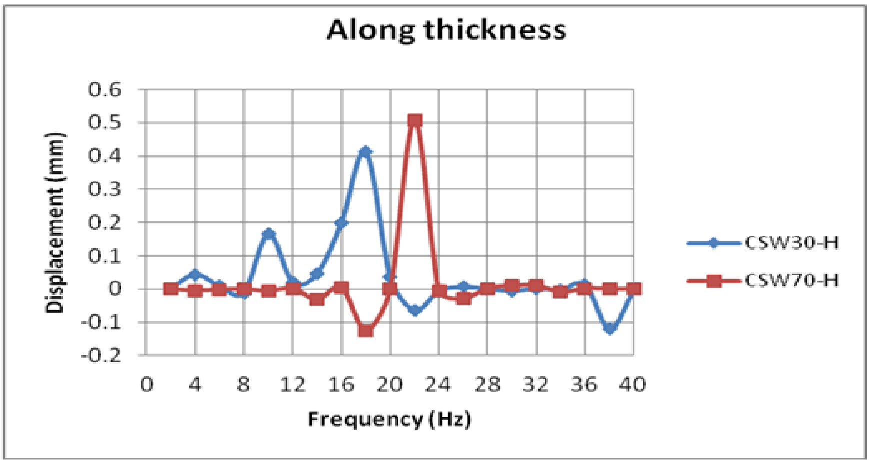


Fig. 13. Displacement frequency performance.

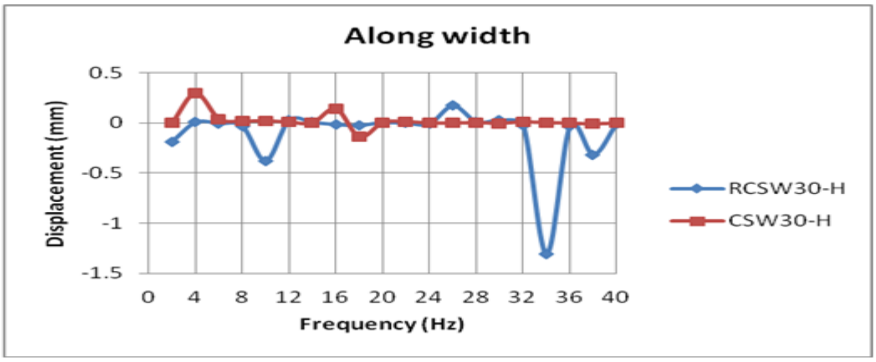


Fig. 14. Displacement frequency performance.

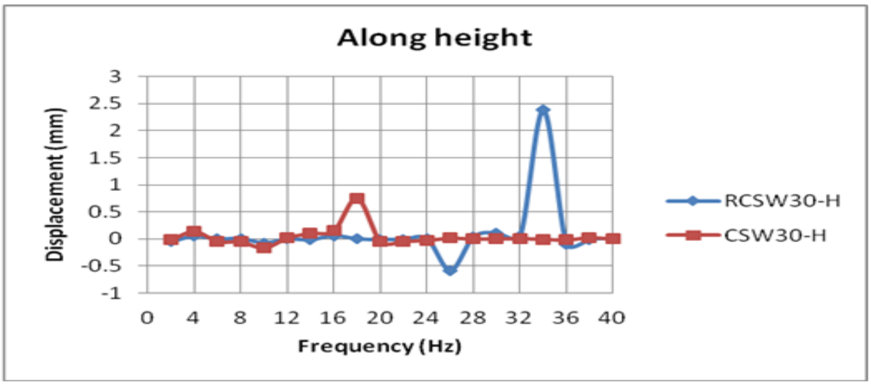


Fig. 15. Displacement frequency performance.

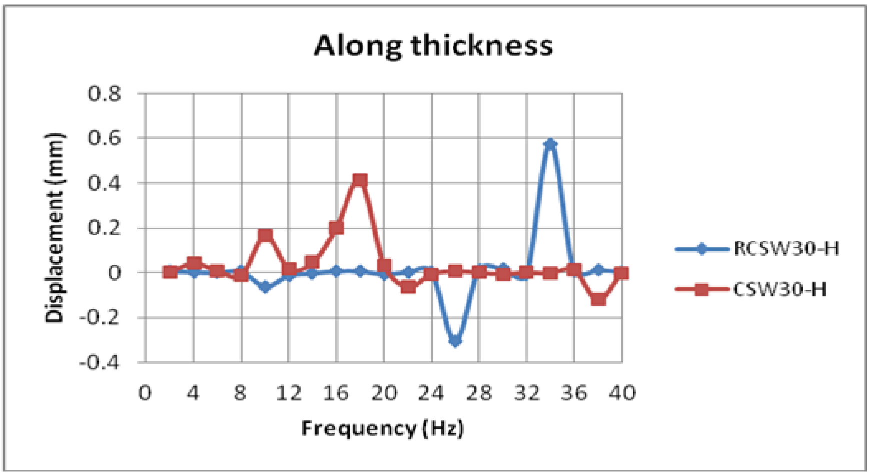


Fig. 16. Displacement frequency performance.

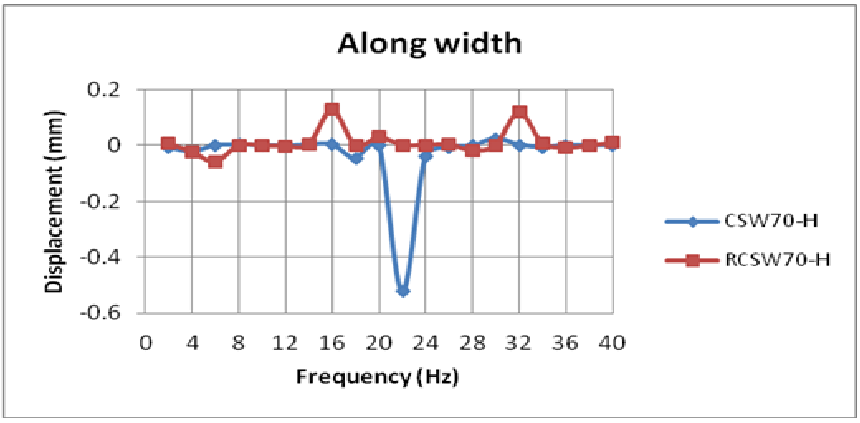


Fig. 17. Displacement frequency performance.

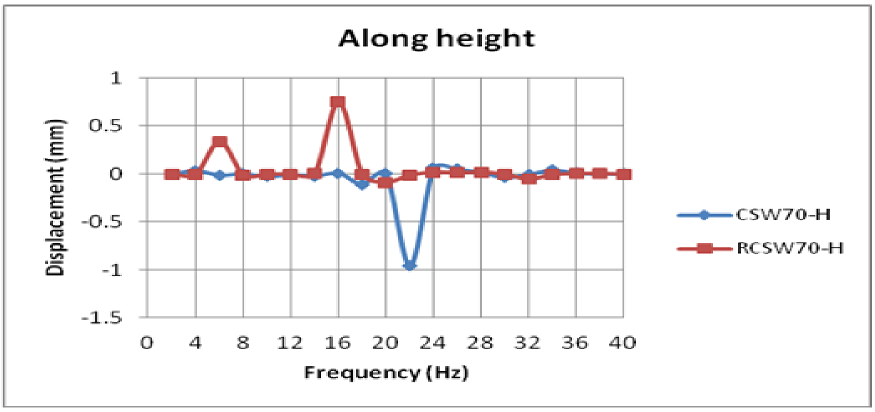


Fig. 18. Displacement frequency performance.

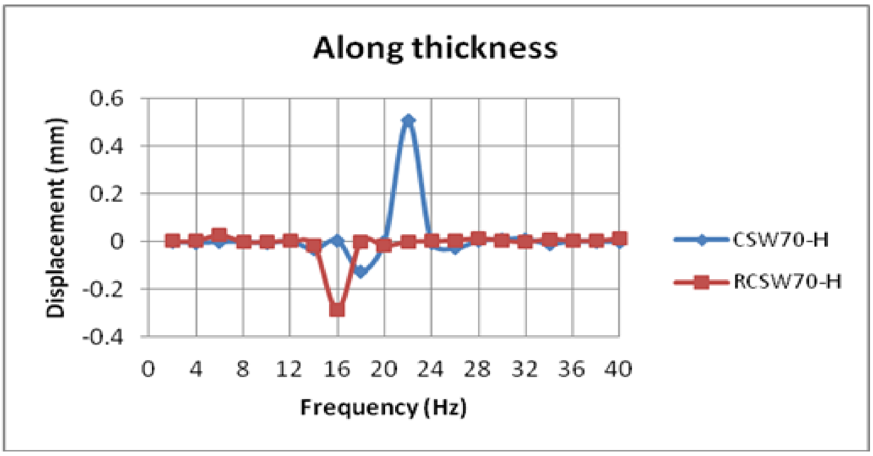


Fig. 19. Displacement frequency performance.

Table 6. Results analysis and comparisons of the models.

Model mark	Maximum displacement along the width (mm)	Maximum displacement along height (mm)	Maximum displacement along thickness (mm)	Decrease %
RCSW30-S	0.0167	0.3468	0.0023	---
RCSW70-S	0.00987	0.2016	0.00129	40.90 72.02 43.91
CSW30-S	0.0164	0.2754	0.0021	---
CSW70-S	0.00996	0.177	0.00147	41.10 35.64 30.00
RCSW30-H	1.305	2.378	0.5761	---
RCSW70-H	0.003	0.0045	0.00146	99.77 99.81 99.74
CSW30-H	0.494	0.7465	0.412	---
CSW70-H	0.0476	0.109	0.126	90.36 85.40 69.42

The dynamic harmonic analysis shows that the displacements increased at a specific frequency that represents the critical frequency that caused maximum displacement in the directions along the width, height, or thickness of the shear wall in case of RCSW or CSW for 30 and 70 MPa as concrete compressive strength. The stiffness of the materials produces an increase in the resonance frequencies in which the compressive strength of concrete and steel sections for columns and steel plate as it has a stiffening effect on an increase of the composite shear wall resonance frequencies. The steel plate and steel columns enhance to increase the concrete shear wall stiffness and gave more resistance against applied static and dynamic loadings.

8. Discussions and Conclusions

Finite element approach was adapted to simulate all reinforced and composite shear walls performance under the influence of static and dynamic (harmonic) loadings. No resonance occurs within the frequency range 0-40 Hz. The interactions between steel columns and steel plate with surrounding concrete need to be correctly designed to maximise the composite action (full interactions). Improvements the full interactions stiffness plays an important parameter due to the slip at the interfaces influences the static and dynamic performance of the composite shear wall.

The displacements RCSW decreased as the compressive strength increase and decreased in CSW when the smart solution is used as presences of steel columns and steel plate. The displacements decreased due to an increase in CSW stiffness due to composite actions under the effects of static or dynamic loading. The limitations of present study as follows:

- The applied frequency range limited to the range of 0-40 Hz

- All parameters such as mechanical properties of all selected materials.
- The applied load.

The models as numerical analysis can be used with different parameters that related to selected problem.

Nomenclatures

C	Viscous damping matrix
K	Stiffness matrix
M	The diagonal mass matrix
U	Displacement
u'	Velocity
u''	Accelerations
ω	Circular frequency of the excitation

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