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Research paper

Parametric Study on Seismic Response of RCS Structures

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Abstract

Reinforced concrete steel (RCS) moment resisting frames consist of structural steel beams joined to reinforced concrete columns. In the last decades, extensive research has been carried out for RCS structures because of the efficiency and economy in application for low to mid-rise structures in moderate to high seismic regions. This study aims to investigate the possibility of improvements or limitations of using RCS composite system for high rise RCS structures in regions of high seismicity. This paper presents the results of a parametric study using a finite element analysis. The study involves both linear elastic time history as well as design response spectrum analyses. The parametric study involves the effect of material (reinforced concrete and steel), plan aspect ratio, floor height and beam span. The findings indicate that the use of RCS composite material not only provides a more economic solution, but also increases efficiency in terms of resilience towards dynamic loadings that the structure may be subjected to due to earthquake actions especially in high seismic regions.

Keywords: *RCS, seismic analysis, Moment-resisting frames, Composite construction, FEM analysis*

1. Introduction

Reinforced concrete steel (RCS) frame construction is growing fast in the modern world. The system consists of steel beams connected to reinforced concrete (RC) columns. In recent years and after the release of the US-Japan cooperative earthquake engineering research program's findings, this type of systems began to be utilized in the industry. In the US, the application of this system includes replacing mid to high-rise steel frame structures with RCS. In Japan, RCS structures are used as an alternative for RC structures in construction of low rise offices and retail buildings to allow for longer floor spans and hence minimizing field labour while maintaining material cost savings provided by reinforced concrete columns [1].

The research on RCD structures focused mainly on seismic analysis in relation to different types of joints such as through column joint, T and L-Shaped joints, and 3D joint tests. 3D-finite element analysis was carried out to investigate the contact behaviour between the reinforced concrete and steel members focusing mainly on stress distribution at the connections. Nevertheless, the research on seismic behaviour of such structures actions on RCS frames. The effects of longer spanning of steel beams or varying floor height in RCS frames subjected to seismic actions were not investigated which form the basis behind adopting this type of composite structural systems [2].

The current research aims at identifying possible advantages or drawbacks for the utilization of RCS structures in relation to that of steel and concrete moment-resisting frames. A parametric study was conducted to investigate the effect of the following parameters on the overall response:

- Floor height.
- Beam span.
- Aspect ratio of building plan.

Existing Research on RCS Structures

Since the release of the US-Japan Cooperative Earthquake Engineering Research Program, the research into composite and RCS structures has increased dramatically. A large amount of RCS related research focused on connectional detailing and analysis, extending the knowledge obtained from the cooperative research program. The assumptions that RC columns behave with full stiffness, even in RCS structures, and that the beams can still span, for distances as long as those in pure steel frames, are used by most of researchers in that field.

Angelo Masi [3] carried out seismic analysis of existing RC structural frames in central Italy. He used artificial as well as natural accelerograms to carry out a non-linear dynamic analysis. The investigation proved the predicted outcome, RC frame buildings displayed unsatisfactory seismic behaviour particularly when they are designed to resist gravity loading solely.

Seyung-Yul Yun et al. [4] carried out a nonlinear dynamic and a reliability theory study to analyse the seismic performance of steel gravity moment frames directly after the earthquake incidents of Northridge (1994) and Kobe (1995). The outcome of the experiment has proven that the seismic capacity of the current steel frame systems is unsatisfactory.

Alessandro Zona et al. [5] conducted a materially-nonlinear finite element formulation study on SCC structures. Results were then validated by conducting quasi-static cyclic experimental test on a benchmark problem. The structure consisted of steel columns joined to either RC or composite beams. Under the application of seismic loads, this type of structure suffered from several issues mainly due to shear at connections. Heavier beams connected to steel columns of low stiffness resulted in very poor performance under seismic action.

Wei Lei et al. [6] carried out a comprehensive review of the researches related to RCS structures based on the mentioned assumptions in order to investigate the beam-to-column connections with the help of finite element techniques. The study proved that integrating RC slabs in RCS structures resulted in a reduced floor depth and weight compared to a typical RC frame affecting the entire structural system including foundation loads. Another study outcome is that the beam-to-column connections have excellent seismic performance. Nevertheless, there was no data collected in relation to the specific gap in knowledge proposed in this study.

Gregory G. et al. [7] based their study on the assumption that reinforced concrete columns still behave with full stiffness in the RCS structures as in pure RC frames. They neglected the fact that the column through beam connection can have an undesirable effect on the entire structural behaviour. Their study involved nonlinear static and dynamic time history analysis and their investigation was limited to connectional behaviour. But, they failed to address the specific knowledge gap proposed in this study.

Sameh S. M. and Gregory G. D. [8] investigated RCS frames using DYNAMIX software by applying push-over method followed by a nonlinear time history analysis. The study proved that RCS frames exceed life safety and near collapse performance levels suggested by existing building codes. However, there was no parametric investigation involved which is the knowledge gap identified to be addressed in this study.

P. Cordova et al. [9] carried out a laboratory test for the largest and most realistic RCS moment frame at that time in order to validate computer simulation models and seismic design provisions for RCS frames. The study involved a nonlinear time history analysis of a similar structure using OpenSees software. Simulation results were compared with laboratory ones and validated. Test results showed excellent seismic behaviour even when designed to test the limits of the current code provisions. Performance of slab along with beams composite action exceeded initial expectations. Precast column connections have proven to be resilient to earthquake attacks. The results showed similarity in trends between the computational analysis and the actual laboratory experiments at low to medium earthquake levels. At higher earthquake levels, there were significant differences in results due to inability of software to model the large local buckles in beams. This error can be reduced by improving the models to better account for local buckling as well as stiffness degradation. Nevertheless, the study did not collect data about the specific gap in knowledge proposed in this paper.

Sameh S. M. and Gregory G. D. [8] conducted several investigations related to RCS frames subjected to seismic loadings. One of their experiments involved static pushover analysis of a 12 story RCS moment frame using DYNAMIX software followed by incremental dynamic analysis. In the analysis, they compared this model to a 6 story steel moment frame and another 6 story RCS moment frame structure described earlier in the same paper. Results showed that RC columns undergo more stiffness degradation under the application of cyclic loading, resulting in higher inelastic deformations compared to steel frames. This may present an issue in increasing floor height using RCS systems. The research laid the grounds for the current study at hands; nevertheless, they failed to collect enough data to address the knowledge gap being investigated in this study.

RCS structural systems show promising future for the construction of structures subjected to dynamic loading in comparison to other alternative construction materials. This has been further backed up by literature from several studies. A research gap was identified in relation to this type of structural systems, where no investigation in relation to parameters of the RCS moment resisting frames was previously done. Therefore, a parametric study was conducted using two different dynamic analysis techniques and the results are presented in the current paper.

2. Methodology

2.1. Finite element modelling of moment resisting frames

With the help of Robots Structural Analysis software, a 15 story moment-resisting frame was designed. The most critical model had 10-meter beam spans, 5-meter floor heights and an aspect ratio of 1:2. The reinforced concrete and structural steel frames were designed in accordance to EN 1991-1-1:2002 as office buildings.

The imposed load was taken as 3 kN/m² while the total dead load was taken as 5 kN/m² for all models. Load combinations were carried out with according to EN 1990:2002 (Eq.6.10 a & b) to obtain the ultimate load. For the reinforced concrete frames, members were designed to be as efficient as possible in accordance to EN 1992-1-1:2004 AC: 2008. Concrete grade of C30/37 with long term properties applied to account for creep and shrinkage effects was used and for the reinforcement yield strength of 500N/mm^2 was used. The same design criteria were applied for the structural steel frame design while referring to EN 1993-1:2005/AC: 2009. Steel grade of S355 was used. Foundation were assumed to be fixed into the ground for all models.

Critical members were identified in both reinforced concrete as well as structural steel models which were used for all models used in the study. For the RCS models, reinforced concrete columns are used with steel beams that have been previously designed concrete and steel frames.

2.2. Model details

A total of 81 models were designed, where each model differs from the others in terms of floor height, beam span, aspect ratio or material type. Table 1 provides a list of variations of parameters used in the study.

Table 1: Variation of Parameters

Parameter/Type	1	2	3
Floor height (m)	3	4	5
Beam span (m)	5	10	15
Aspect ratio	1:1	3:4	1:2
Material	Steel	RC	RCS

Aspect ratios used are shown in Figure 1.

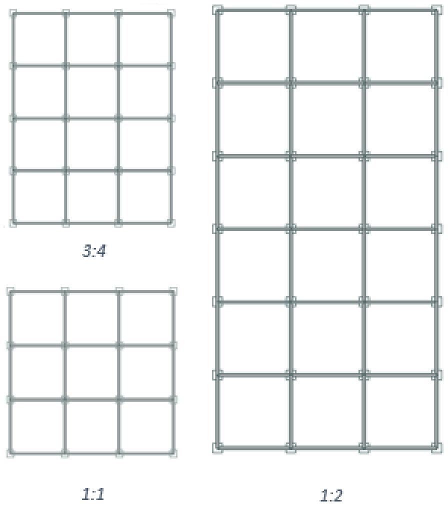

Fig. 1: Aspect Ratio Variations

2.3. Material and sectional properties

The models were prepared in Oasys GSA Suite 8.7 in accordance to the sections extracted from robots-structural analysis software.

For steel frames, CAT UC UC356x406x287 and CAT UB UB533x210x122 with S355 steel grade were used for columns and beams respectively. For RC frames, square columns sections of 650 mm x 650 mm were used with 3.8% reinforcement ratio. Rectangular beam sections of 600 mm depth x 300 mm width were used with 3.2% reinforcement ratio.

For RCS frames, square RC columns sections of 650 mm x 650 mm were used with 3.8% reinforcement ratio. For beams CAT UB UB533x210x122 with S355 steel grade were used.

All nodes were assumed to be restrained in all directions except for the minor axis where the dynamic loading was applied.

2.4. Input Earthquake

The peak ground acceleration value as well as the earthquake time history profile were both extracted from the data related to El Centro earthquake that took place in 18th of May 1940. As the earthquake took place in 3 different regions, the profile adopted belonged to El-Centro UP with a peak ground acceleration of -2.06 m/s^2. The earthquake magnitude was estimated to be 7.1. The ground acceleration is shown in Figure 2.

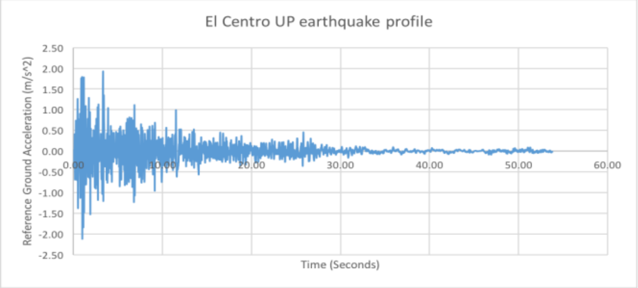

Fig 2: El Centro UP Earthquake Profile

2.5. Dynamics Analysis Methods

2.5.1 Modal analysis

All the analyses were restricted to the first 20 modes as the effect from higher modes are negligible due to the following reasons:

- The analysis is linear elastic in nature.
- The models are of regular and symmetrical nature. No irregularities are present.
- The frame is only 15 stories in height.

2.5.2 Linear elastic time history analysis

The analysis was stopped after the 10th second as the peak earthquake magnitude occurs somewhere after the 9th second. A time step of 0.02 was used.

3. Results and Discussions

Results extracted from Oasys GSA analysis suite were analysed in order to obtain the magnitude of the peak nodal displacements and accelerations. These values formed the skeleton of the discussion section. Graph samples (Figure 3 to Figure 16) are displayed to show the general trend. Minor variations due to dynamic magnifications have been eliminated by analysing a greater number of models.

3.1. Vibrational frequency

3.1.1. Effect of floor height and beam span

The structural vibrational frequency is inversely proportional to both parameters, floor height as well as beam span. Table 2 shows the model details of RC frames for which the results have been presented in Fig.3.

Table 2: Model Details for RC frames

Model Number	Beam Span (m)	Floor height (m)
01	5.000	3.000
04		4.000
07		5.000
10	7.500	3.000
13		4.000
16		5.000
19	10.000	3.000
22		4.000
25		5.000

Furthermore, it is observable that the beam span variations have higher effect on the vibrational frequency in comparison to the variations in floor heights (models 001/010/019 are at a different zone in comparison to models 004/013/022 and the same trend .occurs for models 007/019/025). This is due to the fact that variations in beam spans are larger in magnitude in comparison to the variations in floor height, which implies that there are more geometrical changes to the structure, and hence, structural mass and dimensions vary more. This can be further explained using the following equation which shows the effect of mass on the structural frequency of vibrations.

$$f = \frac{1}{2\pi}\sqrt{\frac{K}{M}} \qquad (1)$$

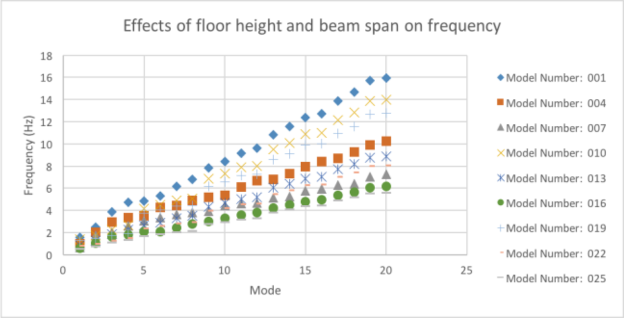

Fig. 3: Effect of Floor Height and Beam Span on Frequency

3.1.2. Effect of aspect ratio

Increasing the structure's aspect ratio results in a direct decrease in the structure's vibrational frequency which can be further related to Equation 1.

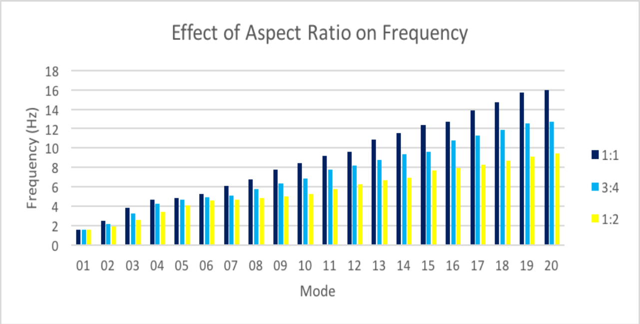

Fig. 4: Effect of Aspect Ratio on Frequency

3.1.3. Effect of construction material

Structural steel frames have higher stiffness value, which in turns make their vibrational frequency higher than those of reinforced concrete frames of same geometrical properties. RCS frames has a magnitude of vibrational frequency closer to reinforced concrete material in comparison to the structural steel. This finding shows that RC is more influential in terms of structural behaviour in the composite structure.

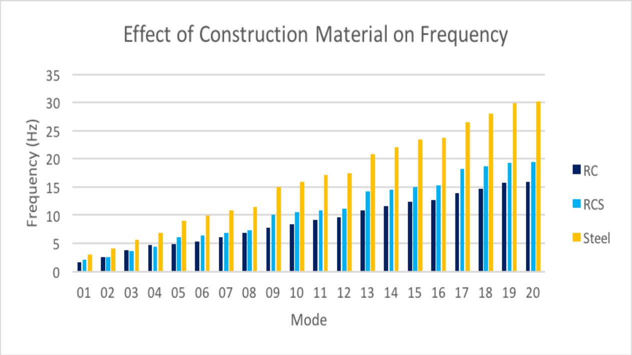

Fig. 5: Effect of Construction Material on Frequency

3.2. Displacement and acceleration

3.2.1. Effect of floor height

Table 3 shows the model details.

Table 3: Model Details for different floor heights

Model No.	Aspect ratio	Floor height (m)
001	1:1	3.000
002		4.000
003		5.000
004	3:4	3.000
005		4.000
006		5.000
007	1:2	3.000
008		4.000
009		5.000

Reinforced concrete (RC)

A direct relationship between floor height and peak nodal displacement is observed. It is clear that the reinforced concrete models experience much higher nodal displacement and much lower nodal acceleration in comparison to the structural steel models. As for the resulting peak nodal acceleration, it decreases as the floor height increases.

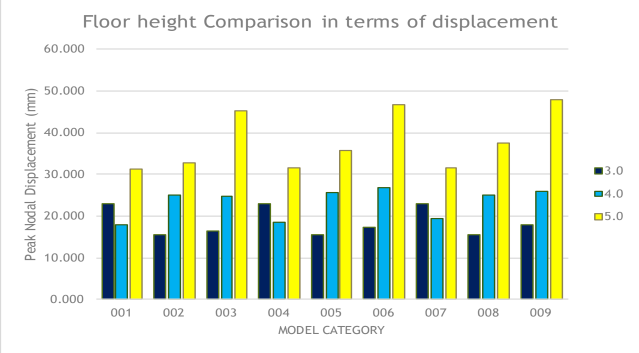

Fig. 6: Effect of Floor Height on RC Frame Displacement

Structural steel

It can be seen that floor height has a direct relationship with the peak nodal displacement and inversely proportional relationship with peak nodal acceleration.

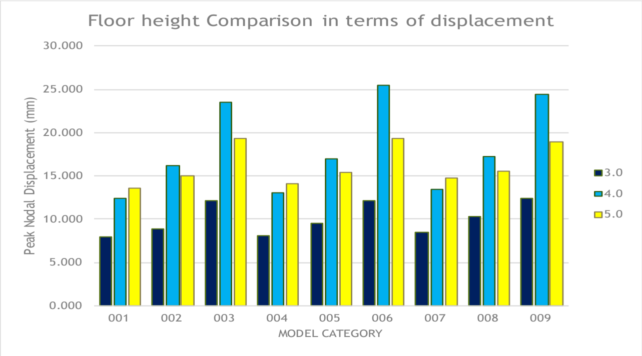

Fig. 7: Effect of Floor Height on Steel Frame Displacement

Reinforced concrete steel (RCS)

The trends emerging in the composite structure are similar to the ones discussed for the other two materials. The dominance in behaviour of the reinforced concrete material can be observed. The range of peak nodal displacements and accelerations is much closer to that of reinforced concrete than of the structural steel which implies that the influence of reinforced concrete in the composite structure is stronger than that of structural steel. The outcome of this section shows a direct relationship between increasing floor height and the resultant displacement.

$$F = ma \tag{2}$$

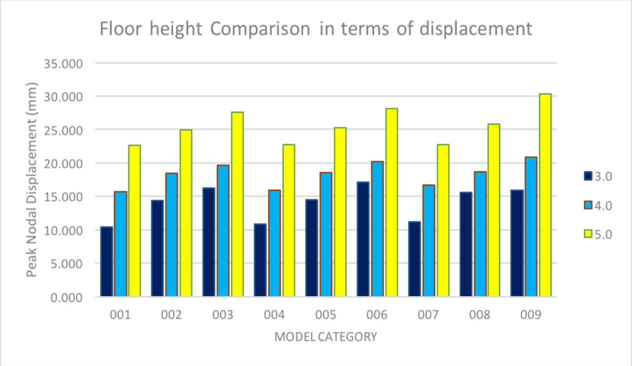

Fig. 8: Effect of Floor Height on RCS Frame Displacement

3.2.2. Effect of beam span

Table 4: Model Details for different beam spans

Model No.	Aspect ratio	Beam span (m)
001	1:1	5.000
002		7.500
003		10.000
004	3:4	5.000
005		7.500
006		10.000
007	1:2	5.000
008		7.500
009		10.000

Reinforced concrete (RC)

A direct relationship is observed between increasing the beam spans and the increase in peak nodal displacement. While an inverse relationship is observed for the peak nodal acceleration case where increasing the beam span results in a direct decrease in the peak nodal acceleration.

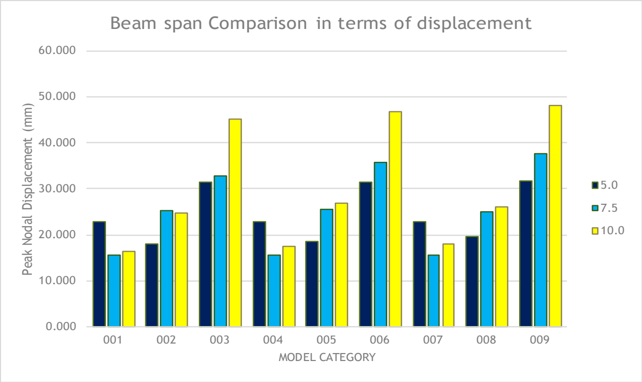

Fig. 8: Effect of Beam Span on RC Frame Displacement

Structural steel

Similar trends emerge in the structural steel case where Increasing beam spans result in a direct increase in the peak nodal displacement of the structure, while for peak nodal acceleration, it seems to have a minor decrease on it.

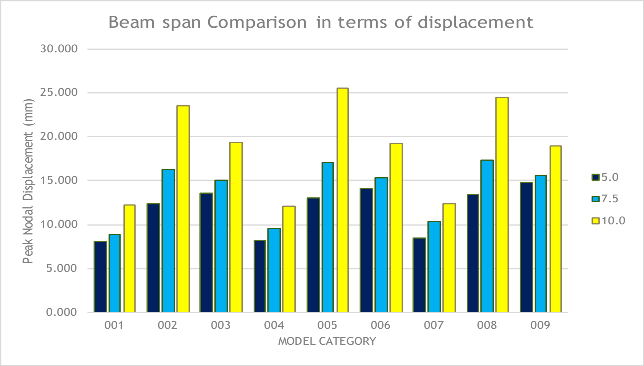

Fig. 9: Effect of Beam Span on Steel Frame Displacement

Reinforced concrete steel (RCS)

For the peak nodal displacement, trends similar to the other two materials emerge. While for the peak nodal acceleration, a varying trend is observed showing the combined effect of the two construction materials within the composite structure.

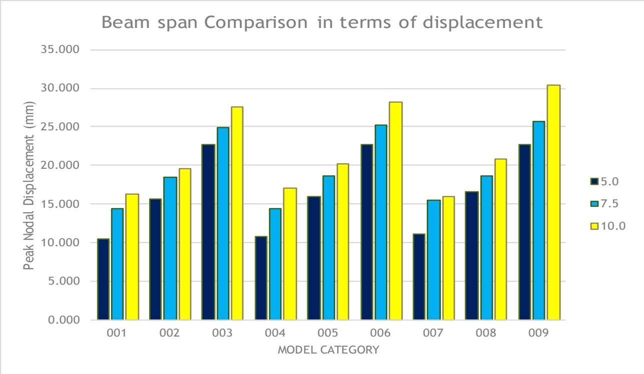

Fig. 11: Effect of Beam Span on RCS Frame Displacement

3.2.3. Effect of aspect ratio

Table 5: Model Details for different aspect ratio

Model No.	Beam Span (m)	Floor Height (m)
001	5.000	3.000
002		4.000
003		5.000
004	7.500	3.000
005		4.000
006		5.000
007	10.000	3.000
008		4.000
009		5.000

Increasing the aspect ratio has a minor effect on the peak nodal displacement or acceleration. The displacement increases slightly while the acceleration decreases. Nevertheless, the changes are not significant.

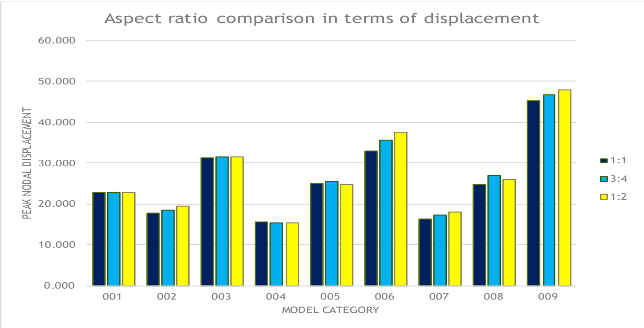

Fig. 10: Effect of Aspect Ratio on RC Frame Displacement

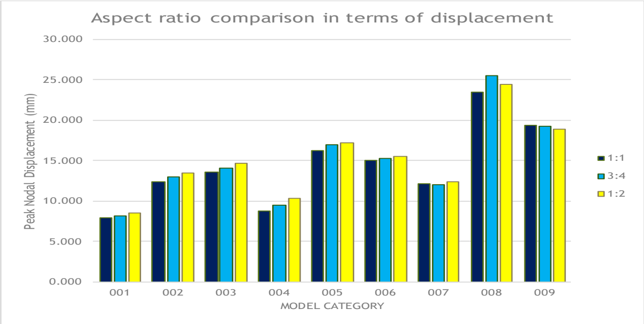

Fig. 11: Effect of Aspect Ratio on Steel Frame Displacement

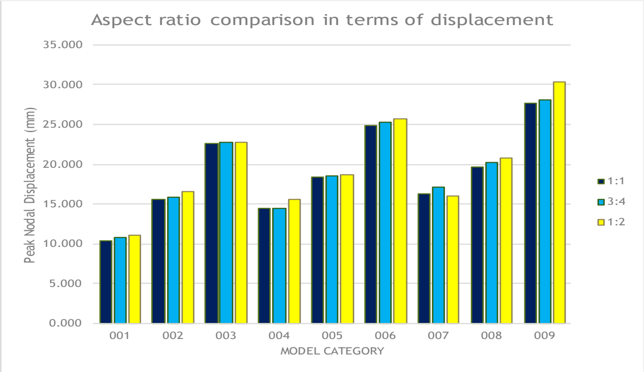

Fig. 12: Effect of Aspect Ratio on RCS Frame Displacement

6.2.4. Effect of construction material

Table 6: Model Details for Different Construction Material

Model No.	Beam Span (m)	Floor Height (m)
001	5.000	3.000
002		4.000
003		5.000
004	7.500	3.000
005		4.000
006		5.000
007	10.000	3.000
008		4.000
009		5.000

Displacement

RCS material shows an intermediate (most of the RCS results are in-between the other two construction materials in magnitude) behaviour between reinforced concrete and structural steel. Reinforced concrete has the highest overall peak nodal displacement among the three of them.

Acceleration

The peak nodal acceleration experienced by the RCS material is in-between the other two materials, with the structural steel models experiencing higher nodal acceleration. It seems that a combination of both materials through RCS composite systems should provide an in-between effect in terms of acceleration and displacement. In addition to that, the magnitude of the peak nodal displacements and accelerations for RCS structures are much closer to those of reinforced concrete than structural steel.

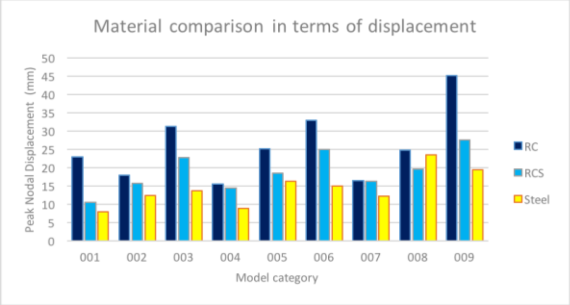

Fig. 15: Effect of Construction Material on Displacement

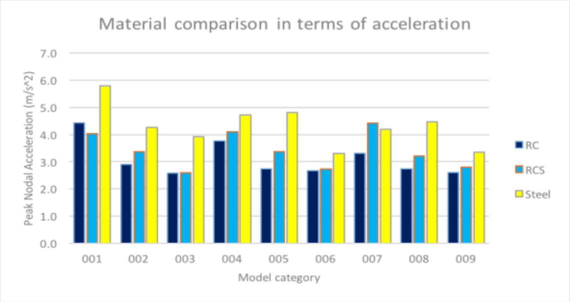

Fig. 16: Effect of Construction Material on Acceleration

3.3. Summary

Effect of Floor Height

- Increasing floor heights results in a direct increase in the general displacement.
- Increasing floor heights results in a direct decrease in general acceleration.
- Increasing floor heights results in a direct decrease in the structure’s vibrational frequency.

Effect of Beam Span

- Increasing beam spans results in a direct increase in the general displacement.
- Increasing beam spans results in a direct decrease in the general acceleration.
- Increasing beam spans results in a direct decrease in the structure’s vibrational frequency.

Effect of Aspect Ratio

- Increasing the building’s aspect ratio results in a direct increase in the general displacement. However, the increase is barely noticeable in comparison to the total displacement that the structure is subjected to.
- Increasing the building’s aspect ratio results in a direct decrease in the general acceleration. However, the decrease is barely noticeable in comparison to the total acceleration that the structures’ nodes are subjected to.
- Increasing the building’s aspect ratio results in a direct and significant decrease in the structure’s vibrational frequency.

Effect of Construction Material

- RCS material exhibits displacement and acceleration responses in-between the other two materials as previously discussed.

4. Conclusion

RCS composite structures have proven to have several merits when used to replace traditional construction material in high rise buildings subjected to seismic loading. Previous research has investigated the use of similar systems for low to mid-rise structures subjected to seismic loading, as well as numerous research was conducted to optimize the connection details. Nevertheless, in this study, we were able to expand on what has already been done and start filling a certain gap in knowledge. High rise structures form the bases of the future as they support the concept of cities growing vertically instead of horizontally in order to maximize the land use and help preserve what is left of the natural habitat of our planet.

The use of RCS composite material not only provides a more economical solution, but a more redundant and efficient one in terms of resilience towards dynamic loadings that the structure may be subjected to due to earthquake actions especially in high seismic regions. By combining reinforced concrete and structural steel together, dynamic magnification effects that each of them separately may be subjected to can be avoided. Furthermore, the intermediate response between both materials means that the structure is subjected to smaller displacements compared to reinforced concrete structures of similar geometrical properties, which leads to less cracking, less structural damage and a more resilient structure. The structure also experiences lower peak acceleration values in comparison to structural steel models which means smaller lateral force in magnitude in comparison to this type of structures.

The main points of this study were to investigate the assumptions of whether RCS structures can still have beam spans as long as those of steel structures and have stiff columns as those of reinforced concrete structures while increasing floor heights. From the results obtained, it is safe to conclude that RCS structures show a promising future as the initial assumptions have been backed up by the findings from this research. Further studies are required in order to fully back up the theories presented in this paper, nevertheless, promising results were obtained.

Acknowledgement

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