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Feasibility of Using Lightweight Load-Bearing Panel Systems in Duplex Apartments of Tall Buildings

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Abstract: As an inevitable result of the growing population in recent times, the requirements of housing facilities, land scarcity, and overexploitation of natural resources have created many problems. One solution for the lack of land is to have multi-storey apartment buildings. Hence, over the last few decades, the number of tall buildings has seen an exponential increase. The apartment spread over two floors, is considered upmarket due to the larger floor area. However, one factor that has been a huge obstruction to promoting duplex apartments is the higher cost. In this study, a novel concept is introduced where a proper load-bearing floor is needed only once on two floors. The duplex is double-height, using lightweight concrete panels supporting lightweight concrete floors. Recycled expanded polystyrene (REPS) based light-weight panels are used as the load-bearing walls, and the NERD slab system is introduced for the intermediate floor. The structural performance was assessed using the comparison of two finite element models for duplex and conventional concepts. It was observed that the duplex concept is structurally feasible in comparison with the conventional concept. The study emphasises that an approximately 30% dead load reduction in typical floor levels has occurred due to the lightweight beam slab system in between floors.

Keywords: EPS Lightweight wall panel, Duplex apartment, Tall building

1. Introduction

Urban migration and urban sprawl are phenomena that have become quite evident during the last 3 to 4 decades [1]. Today, Sri Lanka is experiencing rapid urban sprawl, and nearly 25% of Sri Lanka's population lives in urban areas. It is expected that 65% of the population will live in urban areas by 2030. This increase will cause urban expansion and create its related issues in these urban areas [2]. A huge increase in the urban population has created many problems in major cities, despite the growth achieved in economic terms.

Many people used to live in suburbs and villages with ample land and surrounded by nature (flora and fauna). Due to urban migration, most of the developable land has already been utilized. There are small individual lands scattered throughout the city that are offered for residential and commercial use at high prices. Hence, high-rise buildings are prompted in urban areas as a solution to land scarcity and an increase in population density [3]. However, with urban migration, many have become confined to blocks of flats with one, two, or three bedrooms in each apartment. The common practice is to locate these apartments within a floor as compactly as possible, thus maximizing the number of apartments accommodated on each floor. Thus, apartments with a gross area of 50 to 120 square meters have become the norm to assure affordability in Sri Lanka [4].

The apartments spread over two floors are often considered upmarket due to the larger floor areas needed. These two storey apartments are often identified as "Duplex Apartments". Duplex apartments can offer many advantages, like having a greater space with at least two or more washrooms, greater privacy for kids who engage in educational activities, having more balconies that can be used for growing exotic plants or organic farming on pots, etc.

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However, one factor that has been a huge obstruction to promoting duplex apartments is the higher cost associated with a larger floor area. In this research, a concept is presented where a proper load-bearing floor is needed only once on two floors. The Duplex Apartment is developed within the double height using recycled expanded polystyrene (REPS) based light-weight panels supporting light-weight concrete or timber-based floors. Previous literature has shown that REPS panels are used as load-bearing walls in single storey and two storey buildings, as well as partition walls in other buildings [5]. In this research, the details pertaining to a duplex apartment concept developed using REPS-based lightweight panels along with a lightweight beam slab system are presented while paying sufficient attention to explain the peculiarities associated with this novel concept.

2. Objectives

The research utilizes structural analysis for a tall building structure to obtain the following objectives,

- Development of duplex apartments as a cost-effective alternative to conventional apartment buildings.
- Development of a viable special arrangement for a typical apartment complex with due attention to the structural aspects and performing the cost studies to assess the viability.

3. Methodology

The following methodology was adopted to achieve the objectives.

The methodology describes the proposed architectural layout, the formation of a duplex with load-bearing panels, the structural performance, and a cost study.

A typical parking layout and apartment layout were introduced in a way that satisfied the parking and building regulations. An architectural layout that can be adopted for an apartment building with eight apartments per floor was developed. The duplex apartment concept was introduced when developing the apartment floor plans. The viability of post tensioned concrete flat plates on every other floor was investigated, along with the lightweight panel-based load-bearing structure.

The structural performance was investigated based on finite element models. The analysis was done based on a finite element model in MIDAS GEN. Two finite element models were created, considering the conventional concept and the duplex concept. The 57-storey apartment building was used as a case study, and its structural performance was investigated by comparing the obtained results from finite element models. Also, cost-effectiveness of the proposed solution was investigated using the aforementioned case study.

4. The Proposed Architectural Layout

4.1 General Layouts

In Sri Lanka, most modern high-rise buildings are used as residential apartment buildings, and they follow a regular pattern. In high-rise buildings, concrete walls are used as part of the partition walls to carry vertical loads. The structural components were arranged considering the architectural requirements, and they will not obstruct the spaces within the building. As a result, regular column grid arrangements are not present in the residential towers as they violate the architectural features. The architectural floor plans were finalized based on parking and building regulations.

4.2 Proposed Parking Floor Plan

The parking levels of the proposed apartment building were arranged considering traffic regulations and building regulations [4]. It is necessary to allow space for vehicle turning circles, ramps, parking stalls, and driveways. The parking level columns and shear walls should be placed in a certain grid arrangement.

The proposed parking level was designed for lightweight vehicles such as cars, vans, two and three wheelers. The relevant regulations for standard vehicle types are mentioned in Tables 1, 2, and 3. The spacing of the columns falls within a regular pattern, mainly due to the clearance required for parking bays and driveways.

Table 1 - Minimum Inner and Outer Turning Radius (Building Regulations, 1999)

	Passenger car
Outer turning radius (m)	7.3
Inner turning radius (m)	4.7

Table 2 - Minimum Width of Aisles (Building Regulations, 1999)

Parking angle (Degrees)	One-way traffic one sided bays (m)	One-way traffic two sided bays (m)	Two-way traffic(m)
0^0Parallel	3.6	3.6	6.0
30^0 Angle	3.6	4.2	6.0
45^0 Angle	4.2	4.8	6.2
60^0 Angle	4.8	4.8	6.4
90^0 Angle	6.0	6.0	6.0

Table 3 - Minimum Dimensions of Car Parking Stalls (Building Regulations, 1999)

Vehicle type	Stall width (m)	Stall length (m)
Standard equivalent (car equivalent also to be used two and three wheels)	2.4	4.8

The proposed apartment building consists of six parking levels, and 46 parking facilities are available on each level. Therefore, 276 parking stalls are arranged within the building. The proposed plan and the grid arrangement for the parking level is shown in Figure 1. The floor height is considered to be 3 m.

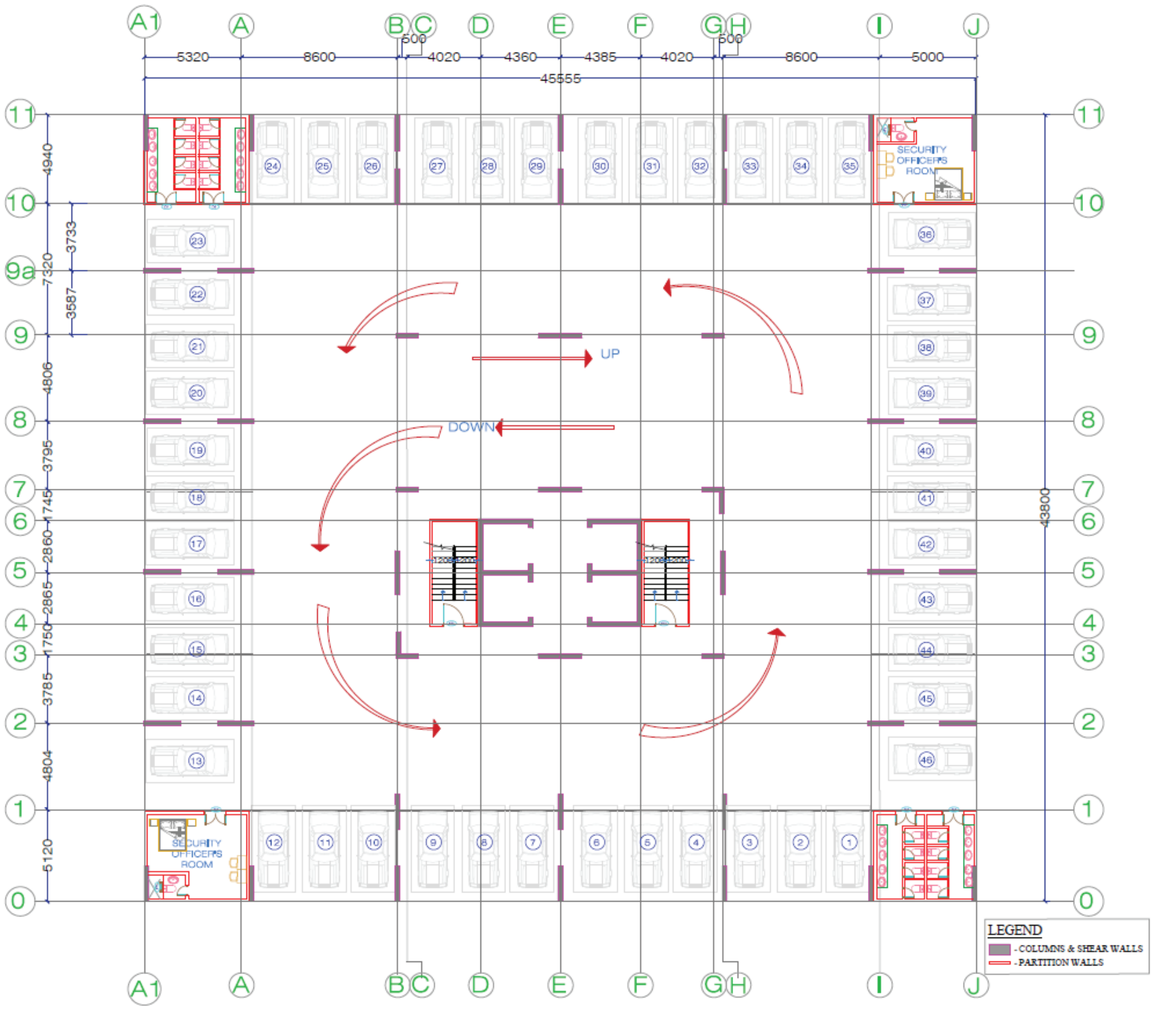

Figure 1 - Proposed Car Parking Floor Plan

4.3 Proposed Apartment Floor Plan

The proposed apartment building consists of 200 housing units at 50 levels. Two floors can accommodate eight duplex housing units. The typical floor and mezzanine (intermediate) floor plans are shown in Figures 2 and 3, respectively. The floor to floor height is considered as 3 m for the residential apartment levels. Therefore, the proposed apartment building total height is 173.5 m. The architectural floor plan of typical apartment level was finalized based on the building regulations.

When arranging a duplex apartment, the pantry and the living room are located downstairs, while the bedrooms and study rooms are upstairs due to privacy issues.

The grid arrangement of the apartment levels is shown in Figures 2 and 3. A different grid arrangement was introduced for the residential floor levels and, as a result, the regular column grid has been changed at the sixth floor level. To keep those different grid arrangements (refer Figures 1 and 2) in the same structure, a transfer plate is introduced (at sixth floor level) in between those grid arrangements.

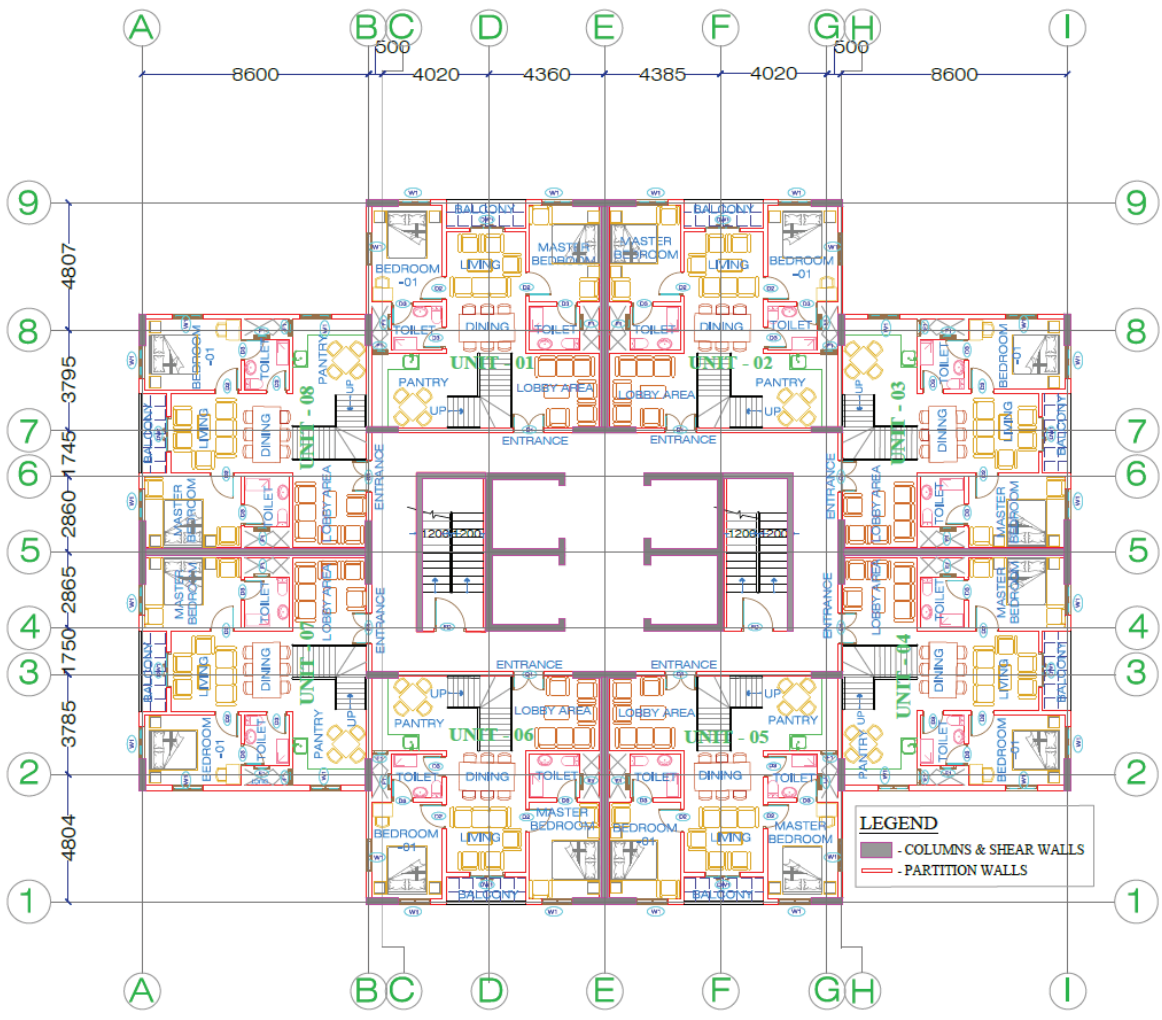

Figure 2 - Proposed Typical Apartment Floor Plan

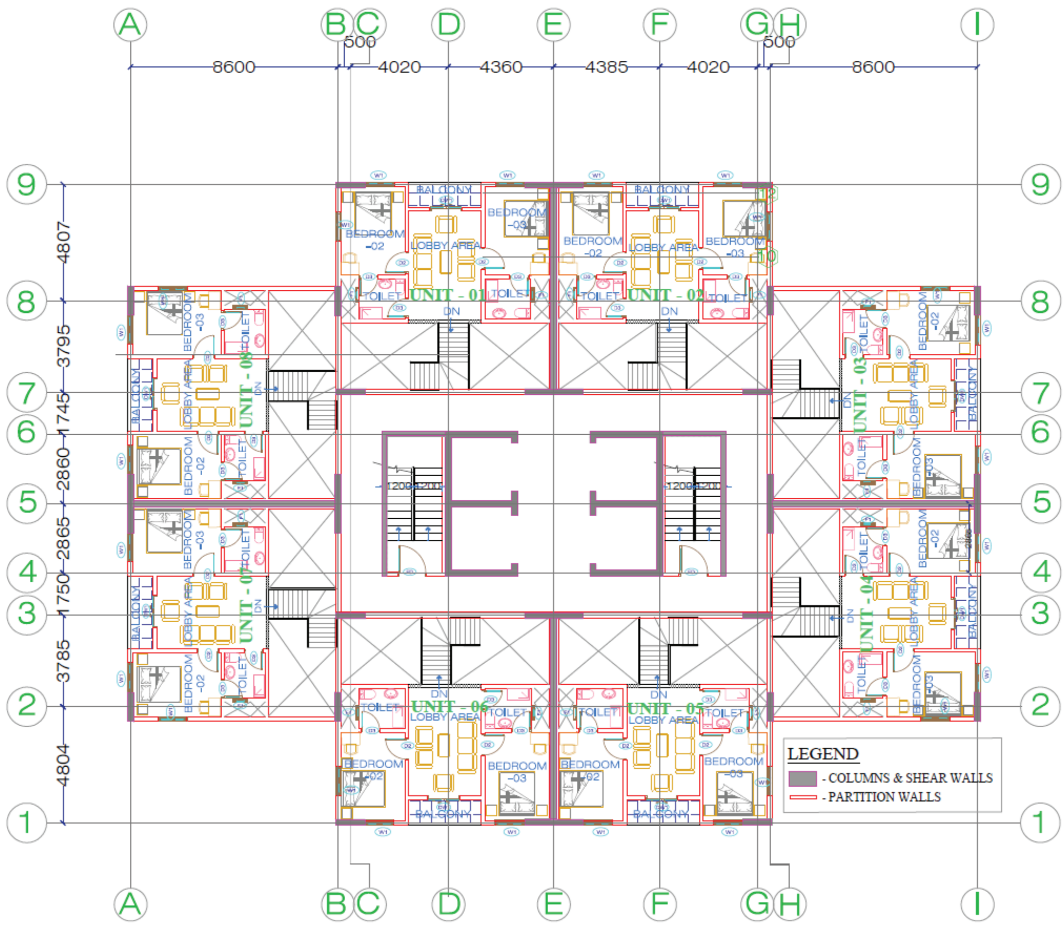

Figure 3 - Proposed Mezzanine (Intermediate) Apartment Level Floor Plan

5. Formation of Duplex with Load-bearing Panels

Recently, recycled expanded polystyrene (REPS)-based lightweight concrete panels are used as load-bearing walls in single storey buildings as well as two storey buildings [5]. From past research studies [6], it has been identified that REPS panels (100 mm and 150mm thick) are safe to use as load-bearing walls in two storey buildings. Hence, these REPS panels (100 mm and 150 mm thick) were used as the load-bearing walls in duplex apartments with tall buildings in this study. The density of these REPS panels is around 650 kg/m^3; low density means lower self-weight which leads to lesser compressive stresses on panels and ultimately leading to economical foundation design [7][8].

In this research, a duplex apartment in between floors was developed using the NERD slab system due to its low cost and lightweight. The NERD slab system consists of 50 mm thick in-situ topping retained on trapezoidal pre-stressed concrete beams in 600 mm intervals (Figure 4). Grade 30 concrete for in-situ topping is retained by placing the gauge 10, 50x50 mm welded G.I mesh as the reinforcement for the slab, and grade 40 concrete is used to cast the pre-stressed beams [9].

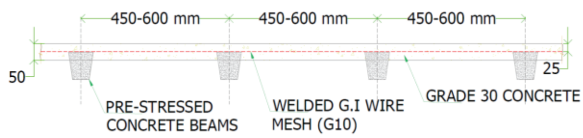

Figure 4 – NERD Composite Slab System

The connectivity and transfer of loads between adjacent panels are mainly achieved along the horizontal and vertical connectivity by tongue and groove joints [10]. The EPS panels are bonded together with tongue and groove arrangements (Figure 5) with tile mortar adhesive paste or cement paste [11].

Figure 5 - Connectivity of EPS Concrete Panels with Tongue and Groove Joint

Vertical connectivity is achieved using 6 mm diameter galvanized mild steel rods (Figure 6). To maintain the good connectivity of panel joints, they have to be glued to each other using a mix of construction grout and Portland cement.

Figure 6 - Connectivity of EPS Concrete Panels with Dowel Bars

The proposed floor plans of a duplex house, with lower and upper levels, are shown in Figures 7 and 8.

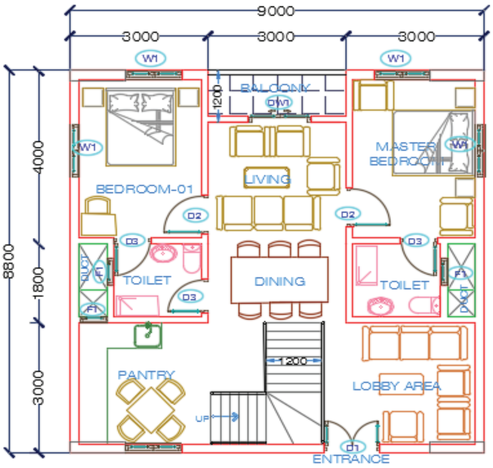

Figure 7 - Lower Floor Plan of Duplex Apartment

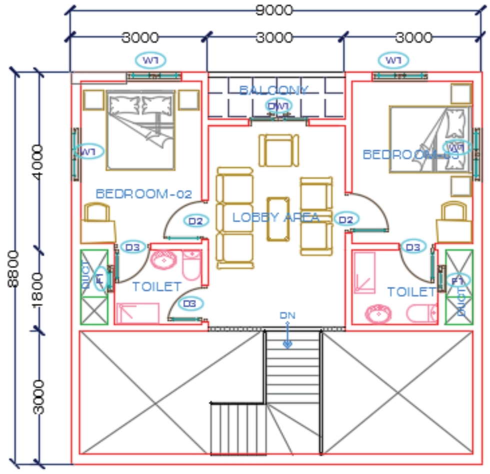

Figure 8 - Upper Floor Plan of Duplex Apartment

The thickness of outer and inner walls of the duplex house were 150 mm and 100 mm, respectively. The formation of a duplex house with load-bearing REPS panels and a lightweight NERD slab system at the intermediate level was introduced in this study.

6. Structural Performance

6.1 Structural Arrangements

The structural layouts were finalized considering the proposed architectural layouts. The podium levels (car parking floors) are designed with 150 mm thick reinforced concrete slabs (Figure 9).

Each typical floor level of conventional building was designed as a 225 mm thick post-tensioned slab (Figure 10). The duplex building's 250 mm thick post-tensioned floors are used only once in two floors (Figure 11). The in-between floor was designed with lightweight materials supported by REPS-based lightweight concrete panels. The NERD slab system was introduced for the in-between floors (Mezzanine floor level –refer Figure 12). Also, the lift lobby area is intended as a 150 mm thick reinforced concrete slab on each floor level.

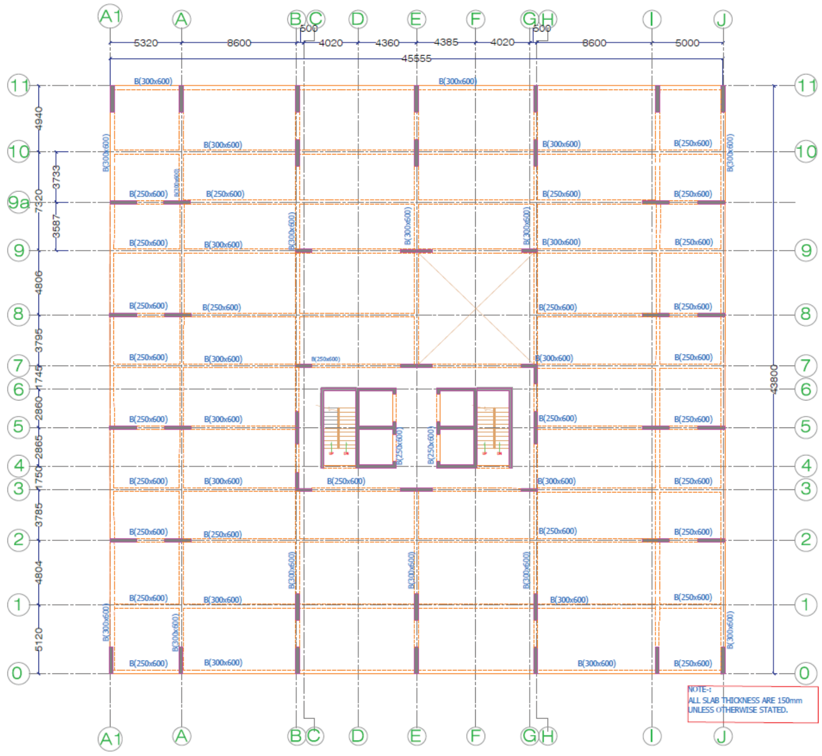

Figure 9 – General Arrangement of Parking Levels

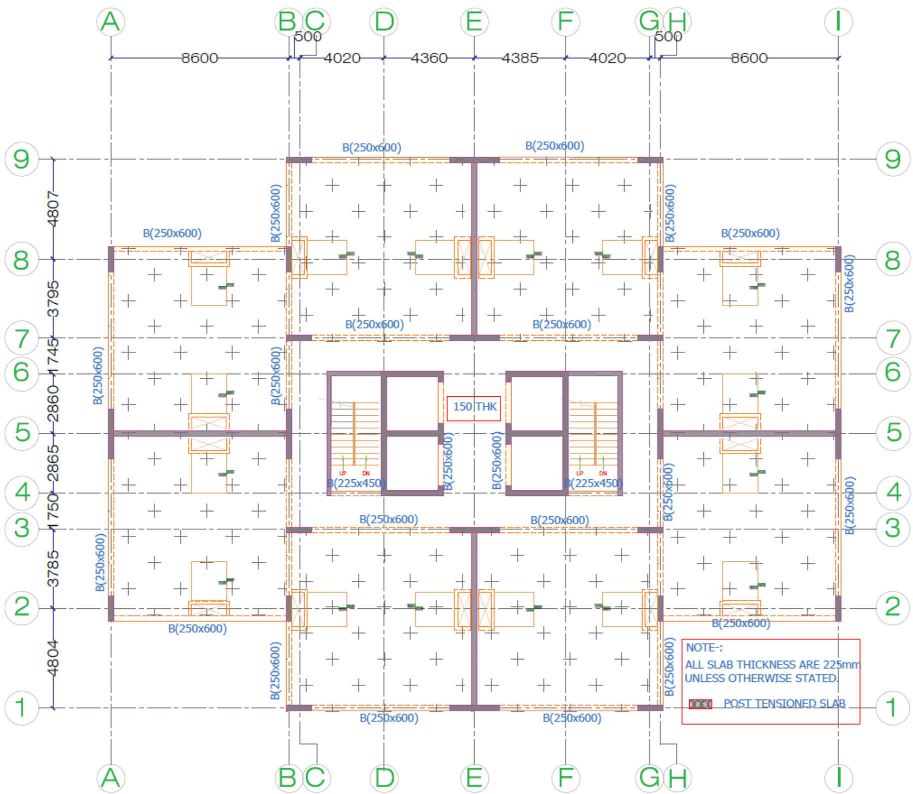

Figure 10 – Conventional Building General Arrangement of Apartment Level

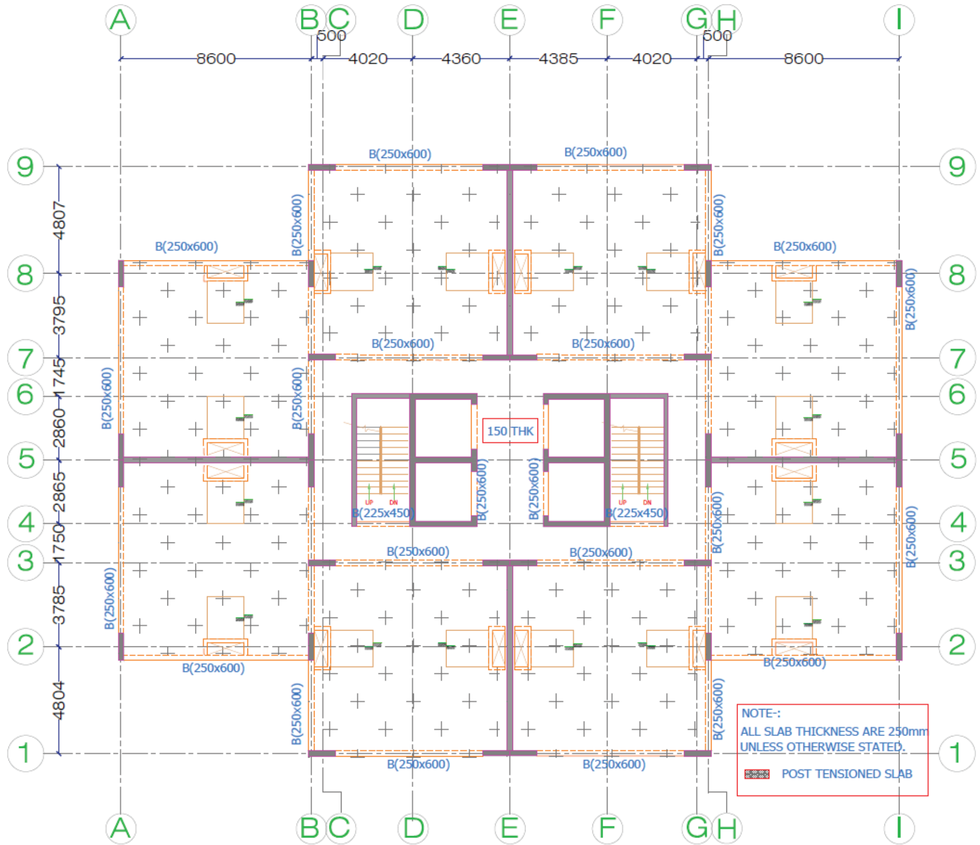

Figure 11 – Duplex Building General Arrangement of Typical Floor Level

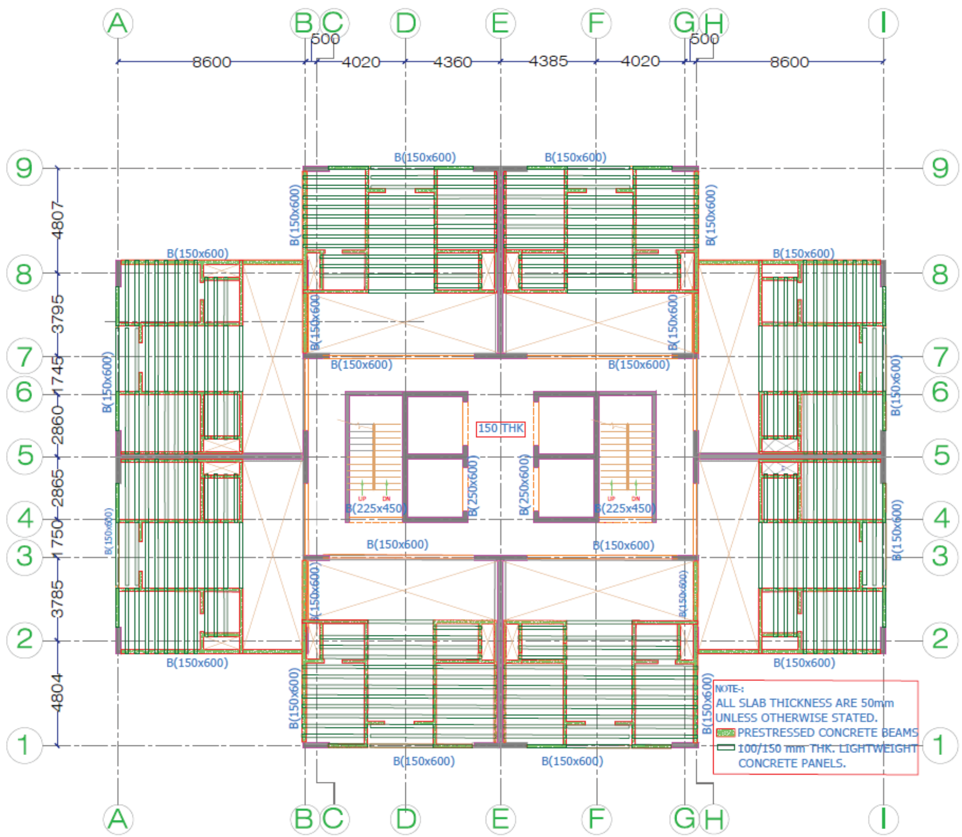

Figure 12 – Duplex Building General Arrangement of Intermediate Floor (Mezzanine) Level

6.2 Structural Model with MIDAS GEN

The complete modeling was carried out using MIDAS GEN 2021 software. The selected structural system is a moment frame with shear walls, an essentially complete space frame supporting gravity loads. The shear walls resist the lateral loads generated by external forces such as wind and earthquakes.

Two different finite element models were created, considering the conventional type (Model B) and duplex type (Model A) apartment buildings (Figures 15 and 16). The superstructure is designed as a reinforced concrete structure. The different grid arrangements were introduced for the apartment and parking levels. The transfer plate is used at the sixth floor level to collect the vertical load from the upper floors, then transfer and distribute it to widely spaced columns that support the transfer plate.

When developing the finite element model, an intermediate level slab, beams and REPS panels loads are applied to the strong Post tensioned slab (lower floor slab). The loads from the occupants are transmitted through the NERD slab, beam, and lightweight EPS panels down to the post-tensioned slab (duplex apartment lower slab level). The structural arrangement of typical apartment level and intermediate level (model A) are shown in Figures 13 and 14, respectively.

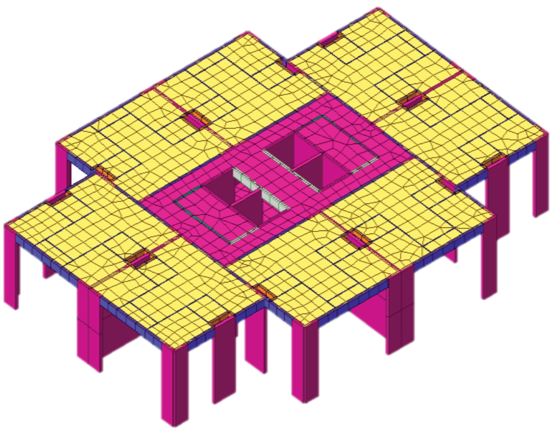

Figure 13 – Structural Arrangement of Typical Floor (Post Tensioned Concrete Floor)

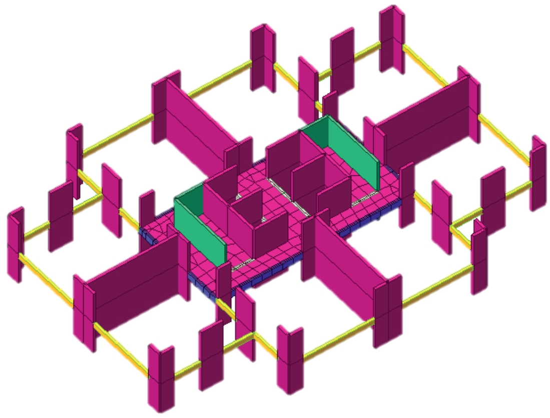

Figure 14 – Structural Arrangement of Intermediate Floor

6.3 Loadings

Many Sri Lankan engineers use different international standards to design buildings. The following codes were used for this study considering the most popular practice in Sri Lanka (Table 4).

Table 4 – Design Codes and Standards

Criteria	Design code/ standard
Dead and Imposed Loads	EN 1991-1-1 Part I (2002) [12]
Wind Loads	IS 875 Part 3 (2015) [13]
Seismic Loads	IS 1893 Part 1 (2016) [14]
Concrete Structure Design	EN 1992-1-1;(2004) [15]
Foundation Design	EN 1997- 1(2004) [16]
Post Tensioned Design	EN 1992-1-1;(2004) [15] TR43: Post-tensioned concrete floors-Design Handbook [17]

Dead loads and imposed loads on selected apartment buildings were calculated using the EN 1991-1 Part I [12] Eurocode standard. The loadings were applied considering the categories of uses in the respective areas. The section properties of different structural elements used in the finite element model are shown in Table 5.

Table 5 - Section Properties of Structural Elements

Section	Dimensions	Concrete grade
RCC Beams	300 x 600/250x600	C 40/50
Shear walls /Column (lift walls)	200 mm, 250 mm, 300 mm thick	C 50/60
Flat Slabs	200 mm, 225 mm, 250 mm thick	C 40/50
RCC slabs	150 mm thickness	C 40

Two different analyses were carried out for conventional and duplex apartment models to do a comparative study. Further, in the analysis, fifty-four different load combinations were introduced.

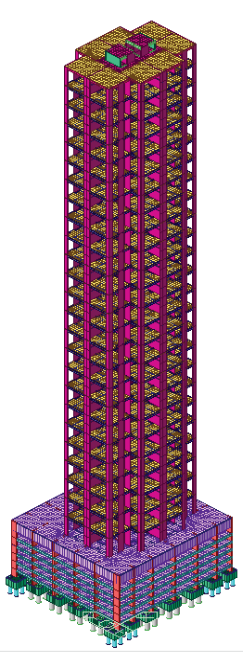

Figure 15 - 3D View of Model A

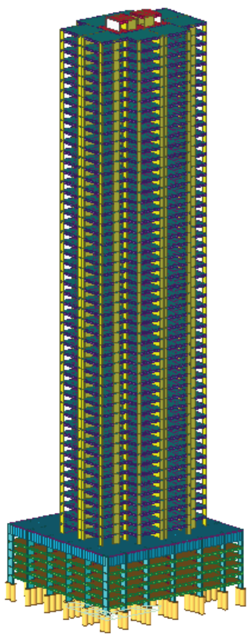

Figure 16 - 3D View of Model B

7. Results and Discussion

7.1 Building Displacements

Considering the conventional and duplex apartment finite element models (models A and B), building displacement values are tabulated in Table 6. From the results in Table 6, it can be seen that there is no major difference in deflection between conventional and duplex apartment structures.

Table 6 - Analysis Results of Displacements

Parameter	Model A	Model B
Transfer Floor Wind Y - dis. Y	4.6 mm	6.1 mm
Transfer Floor Wind X – dis. X	5.1 mm	6.6 mm
Transfer Floor Spectra X – dis. X	0.1 mm	0.18mm
Transfer Floor Spectra Y – dis. Y	0.5 mm	1.3 mm
Roof Floor Wind Y – dis. Y	235.8 mm	189.5 mm
Roof Floor Wind X – dis. X	170.1 mm	109.5 mm
Roof Floor Spectra X – dis. X	0.9 mm	2.6 mm
Roof Floor Spectra Y – dis. Y	20.1 mm	25.1mm
Maximum displacement	235.8 mm	189.5 mm
Maximum allowable displacement (H/500)	=173.5 m/500 =347 mm	
Maximum allowable displacement H/500 (=347 mm)	>Maximum displacement Model A (=235.8mm)	
	>Maximum displacement Model B (=189.5mm)	

(* displacement – dis.)

In the comparison of models A and B, the lateral and seismic displacement values are fairly low at the transfer floor level. The lateral displacement at the roof floor level is comparatively higher in model A (the difference is 50-70 mm). The maximum allowable displacement value is 347 mm (H/500) [18] at top of 173.5 m height building. Therefore, model A and B lateral displacement values are in the acceptable limit state (H/500).

7.2 Fundamental Period of Vibrations

The mass used for dynamic analysis is 100% for dead loads and 25% for live loads. Thirty modes were used to perform the Eigenvalue analysis to ensure more than 90% mass participation.

All modes are combined using the Complete Quadratic Combination Method (CQC Method). Table 7 shows the model A and model B fundamental period of vibration values, and there is no major difference as per the results.

Table 7 – Fundamental Period of Vibration Results

Mode shape	Fundamental period of vibration model A		Fundamental period of vibration model B	
	Frequency (Hz)	Period (sec)	Frequency (Hz)	Period (sec)
Mode 1	0.1501	6.6636	0.1464	6.8309
Mode 2	0.1767	5.6588	0.1546	6.4691
Mode 3	0.1887	5.3000	0.1825	5.4803
Mode 4	0.4934	2.0266	0.4573	2.1867
Mode 5	0.7065	1.4154	0.6309	1.5851

7.3 Pile Reaction Values

Considering the serviceability limit state in Models A and B, the column base reaction values are shown in Figures 17 and 18, respectively.

The column base reaction values are considerably lower in the duplex-type apartment concept (model A). To compare the results, the same soil condition was assumed for the duplex and conventional methods. The required size of the piles and number of piles used were calculated considering the vertical load applied.

Hence, the duplex concept of substructure design is cost-effective in comparison with conventional concepts. According to the obtained computer analysis results, the duplex concept is structurally feasible.

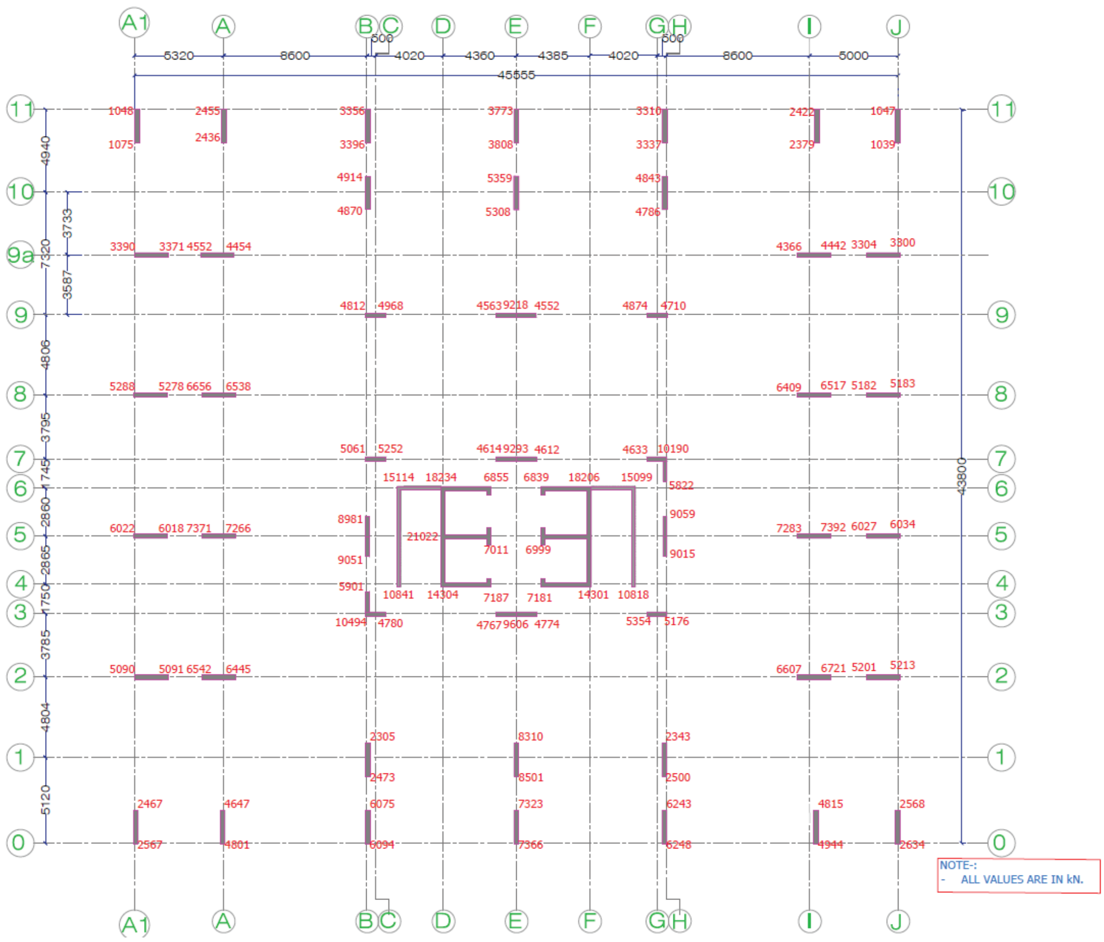

Figure 17 – Duplex Building Column Reaction Values (Serviceability Limit State)

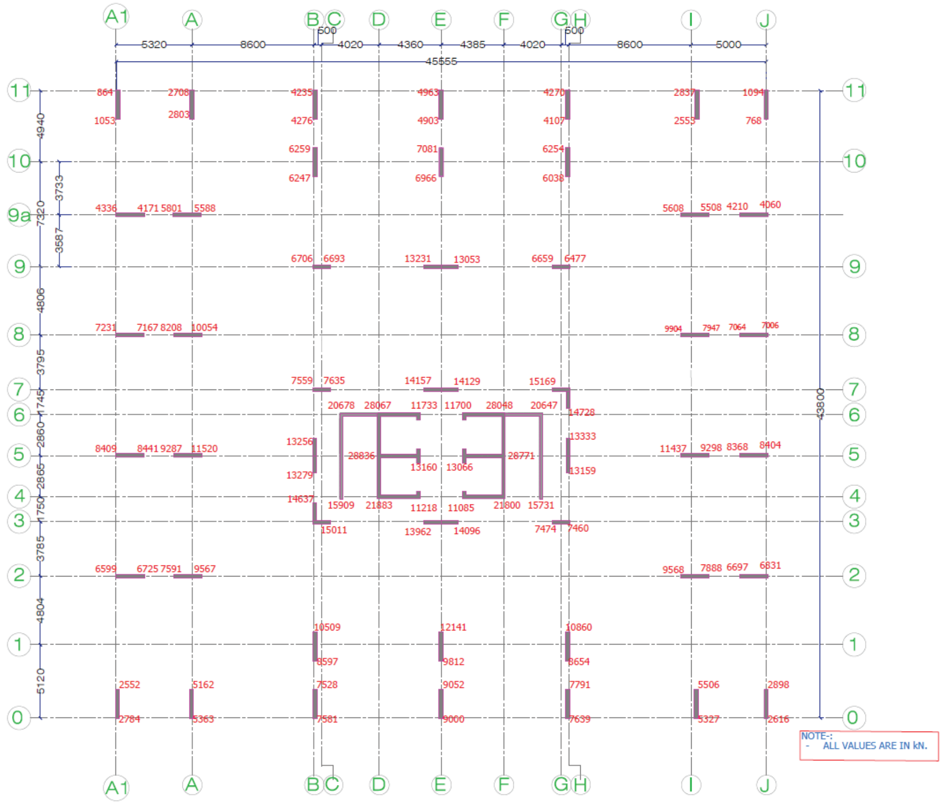

Figure 18 – Conventional Building Column Base Reaction Values (Serviceability Limit State)

8. Cost Study

The load comparison for the transfer plate of the conventional and duplex methods are summarised in Table 8. One of the key findings is that duplex concept can reduce the dead load on the transfer plate. When we reduce the total load, additional moments also decrease. Because of that, the duplex concept transfer plate is more cost effective than the conventional building. Hence, this is practically feasible.

Table 8 - Comparison of Conventional and Duplex Concepts Loads due to Self-weight

	Conventi-onal concept (kN)	Duplex concept (kN)	Dead load reducti-on
Typical floor slabs load	186 478.3	124 400	33%
Load from walls	129 324.7	41 452	68%
Total load transferred to transfer floor	315 803	165 852	47%

(Note: The comparison was carried out considering the partition walls at typical levels of conventional concept as 150mm thick solid blocks and light-weight REPS walls in the duplex concept.)

The conventional concept introduced post-tensioned slab with thickness of 225 mm on each floor level. The duplex concept introduced strong post-tensioned slab once on two floors with thickness of 250 mm. The intermediate floor of duplex concept was designed with thickness of 50 mm NERD slab system. Hence, the slab reduction is nearly 150 mm. The dead load reduction from the slab is calculated at 33%. When we used lightweight partitions instead of normal partitions, it also reduced the partition's weight. It is calculated at 68% reduction with the cement block walls. The total dead load saving is calculated at 47%. According to the results obtained from FEM analysis, there is evidence that the size and number of piles for the conventional building's pile foundation are increased compared with the duplex building. This is due to the extra weight of concrete and wall loads in conventional buildings. In the duplex concept, a strong post-tensioned slab is used once on two floors. Considering the PT cost, the NERD slab construction cost is low. Comparing these two concepts, duplex concept is cost-effective.

9. Conclusion

Based on the findings, it is evident that the duplex concept with lightweight REPS-based panels and a lightweight floor system is structurally feasible. The intermediate floor was constructed with a lightweight NERD slab system, which is economical compared with post-tension slab construction. The Duplex apartment is developed within the double height using recycled expanded polystyrene (REPS)-based lightweight panels supporting lightweight concrete floors, and it can be constructed in parallel with the above-level post-tension construction works. Hence, the construction time is reduced compared with the conventional concept. However, with the REPS panels as a walling material, the installation process will be faster than with block or brick wall construction due to the tongue and groove technique.

The column base reaction values are considerably lower in duplex concept due to the reduction of dead loads. Hence the duplex concept's substructure cost is lessened compared with the conventional concept. After processing the results of the research, it was concluded that the duplex apartment concept can be used to design economical and better structurally performed structures.

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