Analysis and design of emergency field isolation hospital building using innovative rapidly construction prefabricated units to treat patients infected with COVID-19

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Abstract

Coronavirus pandemic is the most catastrophic phenomena of nature. In a major disaster which affected substantially to human lifecycle and property loss. Instant rehabilitation for the people affected with coronavirus was essential. As an immediate measure, it led to the application of light-gauge steel within Saudi Arabia for quick construction, in addition for the safety purposes during disaster in the forthcoming. Several hospital buildings with changeable categories of earthquake and seismic performance design needs are present. Broadly, the earthquake performance is categorized into two types: structural and non-structural, either under unsatisfactory conditions can be dangerous to occupants in the building once damage occurs. The deprivation in structural support of hospital building's systems (i.e. lateral and vertical force resisting systems) like frames and walls in the hospital building comes under structural damage, whereas the non-structural damage means the damage which doesn't affect the structural support system reliability such as pipes damage and pumps disruption, window breaking, breakdown of chimney viz. Furthermore, the non-structural damage is life intimidating also uneconomical.

Keywords Prefabricated structures · Structural analysis · Light-gauge steel structures

Introduction

Several building types with seismic design requirements and changing performance are present. The earthquake performance in buildings is broadly divided in two types structural and non-structural, either under unsatisfactory conditions can be dangerous to occupiers of the building while the damage occurs. The structural damage refers to the building deprivation with structural support methods (lateral force and vertical resisting methods) like building walls, frames, etc, whereas the non-structural damage means any damage without effecting the uniformity of support system such as the failure of chimney, windows breaking, any destruction of pipes, disturbance of pumps and telecommunication

equipment destruction. [1, 2]. The non-structural damage is life intimidating also uneconomical. The expected form of damage is a difficult concern, which is influenced by the structure configuration, type and age, materials used for the construction, conditions on site, building proximity to neighbouring buildings and the form of non-structural elements [3, 4].

The use of reinforcement is not novel. The outer straps of iron were usually used in stonework. In 1825, the reinforced brickwork was used initially. The masonry providing with reinforced concrete elements in both the ways horizontal and vertical is called as “Confined Masonry”. The masonry structures achieve stability with support of elements like cross walls, floors, roofs. When the load distribution is uniform, the load bearing walls are more efficient, whereas the eccentric loading is eluded with sufficient strength provision to walls, floors, also by giving satisfactory slab stiffness, support fixity. It must be considered throughout the planning stage of masonry structures [5, 6].

The use of steel buildings with light-gauge for agricultural structures, manufacturing works, storerooms and official buildings are common. With a storey height between 1 and 2. The prefab members application has improved the

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height of the building till six storey. The manufacturing of frames using steel having shorter length measurement of the building with repelling lateral forces in form of moment frames are typical, whereas the forces in longer direction are typically counterattacked with the diagonal steel rod bracing. As buildings of such type are lightweight, low rise, also built of steel members generally carry out fine during earthquakes with low collapses. In 2005, the earthquake in Kashmir with a magnitude of 7.6 on Richter scale on the Himalayan western boundary. As an estimate around 780,000 buildings were destroyed or damaged and are reduced to unusable for a long period. Roughly, 17,000 institutional buildings also major hospitals close by epicentre were damaged severely. The aim of this research is to come up with a cost-effective type building with smaller amount of viability to earthquake destructions [7, 8].

This research commenced using the literature available on light-gauge steel or cold-formed steel. Then, the selection of typical hospital building plans was done. Later, the building plan for the particular hospital was designed. A three-storied hospital building was designed by STAAD Pro programme as a light-gauge steel structure confirming the seismic provisions for reinforced masonry of Saudi Building Code.

Cold Form Steel

In England, the first sheet rolling mills were introduced by Henry Cort in 1784 and directed the structural application for first cold-formed steel and industrialized in America well

ahead in 1923 by John Tytus further headed to the current manufacturing on strip coiled steel basis. Also, the corrugated steel sheets with light-gauge for building sheathing. The Fig. 1 depicts the cold form steel building [9, 10].

The principles of design for the light-gauge steel sections

The American Iron and Steel Institute (AISI) initiated conducting research since 1939 which is currently supervised by structural professionals allied by the AISI commissions for the strip and sheet steel manufacturers. The requirement was reviewed and amended frequently from initial publication in 1946 is implemented [11–13].

Design basis at present, the allowable strength design method (ASD) structural design of light-gauge members is briefed and applied. The Fig. 2 illustrates the cold-formed steel framing used for housing [14–16]. The required strengths in allowable strength design method are axial loads, bending moments and shear force, etc., for structural members and are calculated with analysis of structures for working loads. The necessary strength shall not go beyond design strength allowable limit and is given below:

$$R \leq \frac{R_n}{\Omega}$$

where R_n = nominal strength specified in the AISI specification. Ω = safety factor specified in the AISI specification. R = required strength. $\frac{R_n}{\Omega}$ = allowable design strength.

Fig. 1 Cold form steel building

Fig. 2 Structural design of prefabricated cold formed steel for house construction

Table 1 Metric sheeting physical properties

Gauge	Uncoated thickness	Weight		Section properties		Moment of inertia, in ⁴	
		lbs/ft of pile	lbs/ft ² of wall	Sections modulus, in ³		Moment of inertia, in ⁴	
				Per section	Per ft	Per section	Per ft
5	0.209	19.1	11.6	5.50	3.36	9.40	5.73
7	0.179	16.4	10.0	4.71	2.87	8.00	4.88
8	0.164	15.2	9.3	4.35	2.65	7.36	4.49
10	0.134	12.5	7.6	3.60	2.20	6.01	3.67
12	0.105	9.9	6.0	2.80	1.71	4.68	2.85

Based on AISI “Handbook of steel drainage and highway construction products,” 1994

Generally, for design of buildings, the loading criteria are taken into account in such a way that the buildings are identified to meet the combinations of dead load, live load, snow load, and wind load confirming the requirements of a number of model building codes, also geographical requirements of location. The above standard methods of load application and maximum loadings, to use where load requirements are not established by local building codes [17–19]

Table 2 Metric sheeting physical properties

Gauge	Uncoated thickness, in	Weight		Section modulus, in ³ /ft	Moment of inertia in ⁴ /ft
		lbs/ft	lbs/ft ²		
7	0.179	13.86	9.24	2.37	3.56
8	0.164	12.70	8.047	2.13	3.20
10	0.134	10.37	6.91	1.84	2.74

Based on AISI “Handbook of steel drainage and construction products,” 1994

Steel lightweight sheeting

In general, to support the earth pressure on walls of excavations and trenches, the corrugated sheeting is used as beam strength, in addition the column strength for driving. Further, for driving easily, a small end cross section is provided with sheeting [20–23]. The sheeting physical properties are shown in Tables 1 and 2. [24–26].

Modelling, analysis and design criteria

Description of three storey hospital building model

This research portrays the design of earthquake resistant structure using cold formed steel. The structure taken for

Table 3 General characteristics of hospital building

Type of building	Hospital building
Number of storeys	G + 2
Area of the building	5400 Sq. ft
Height of building	44.5 ft
Ceiling height	11 ft
Height of truss	8.5 ft
Sill level	3 ft
Lintel level	7 ft

this thesis is three storey hospital building ground, first and second floor as shown in Fig. 4, 5 and 6, which comes under zone 2A according to building code of Saudi Arabia. Moreover, the structure is also designed for wind loads keeping in view the climatic conditions of the city. The general characteristics of building hospital are mentioned in Table 3.

Architectural drawings of hospital are shown in Fig. 3, 4 and 5.

Loading data

Dead load calculation for three storey hospital building is shown Table 4. Self-weight of sheet comes under dead load for roof. The 24 mm fibreboard with cement, floor finishes with 10 mm screed dead load comprised of first and second floor self-weight was used. Live load calculation for hospital building is shown in Table 5 and 6. Live loads for hospitals are taken from ASCE 7–05. ASCE classifies the hospital as IV and provides with the least live loads. Wind load calculation as shown in Table 7 is generated automatically for the hospital building providing the following details based on;

Fig. 3 Ground floor plan of hospital

Fig. 4 First floor plan of hospital **Fig. 5** Second floor plan of hospital

Code	ASCE-7-02
Building classification	Category IV
Basic wind speed	100 mph
Exposure category	Exposure C
Structure type	Building structure

Seismic loads are calculated based on UBC as shown in Table 8. All other loads are calculated manually using ASCE-7-02, UBC-97 and MBMA.

Description of the section

Stud distances are established subsequently after calculating the moments and vertical loads for which two feet distance

was decent enough for the sheet strength and vertical load. With the additional diagonal strut, the bracing was adequate. Truss spacing is considered with wind load, DL and LL reversal of wind load. The suitable spacing was found as four feet and also decent for the sheets. The anchorage bolts are broadly accepted for the system expansion of bolts for which Hilt and Rawal bolts are used in general for applied strength requirement. The carbon steel which is compliant to ASTM C1513-04 with a diameter of 4.8 mm and self-drilling screw hex head was used. C-lipped section CS3 75 × 090 is applied for all members. The Fig. 6 shows the sectional properties of C-lipped section having web (16 in), flange (3.75 in), lip (0.50 in) and thickness (0.09 in).

Table 4 Dead load calculation for hospital building

Load type	Value	Units
<i>(a) Dead load = Self-weight + superimposed dead load</i>		
(1) Roof sheet		
0.7 mm thick GI sheet	1.126	psf
(2) False ceiling		
Hat section		
Thickness	0.2	mm
Girth	72	mm
Weight	0.2	kg/sq. ft
	0.441	psf
Cement board		
Thickness	4.5	mm
Density	1390	kg/m ³
Pressure	6.255	kg/m ²
Pressure(load)	1.282000576	psf
Total pressure(load of false ceiling)	1.723	psf
(3) Wall cladding and insulation		
Insulation		
Thickness	50	mm
Density	10	kg/m ³
Pressure	0.5	kg/m ²
Pressure(load)	0.102478064	psf
Internal cladding		
Thickness	10	mm
Density	1390	kg/m ³
Pressure	13.9	kg/m ²
Pressure(Load)	2.84889017	psf
External cladding		
Thickness	12	mm
Density	1390	kg/m ³
Pressure	16.68	kg/m ²
Pressure (load)	3.418668203	psf
Total pressure (load of cladding)	6.370	psf
UDL on each stud	12.74007287	lbs/ft
<i>Calculation of dead load at different levels:</i>		
Dead load at roof level (36ft)		
(1)self-weight of truss member		
(2)Roof sheet	1.12623392	psf
(3) False ceiling	1.723000576	psf
Total DL	2.849	psf
Dead load at 2nd floor level (24ft)		
(1) 20 mm ceramic tile	9.427981856	psf
(2) 10 mm screed	7.911306514	psf
(3) 24 mm cement fibreboard	5.697780339	psf
(4) False ceiling	1.723000576	psf
Total DL	24.760	psf
Nodal load for joist	99.04027714	lbs
Dead load at 1 st floor level (12ft)		
(1) 20 mm ceramic tile	9.427981856	psf
(2) 10 mm screed	7.911306514	psf
(3) 24 mm cement fibreboard	5.697780339	psf
(4) False ceiling	1.723000576	psf

Table 4 (continued)

Load type	Value	Units
Total dead load	24.760	psf
Nodal load for joist	99.04027714	lbs

Table 5 Live load for hospital building

Occupancy or use	Value	Unit
Operating rooms	60	psf
Operating rooms(nodal load)	240	lbs
Private rooms	40	psf
Private rooms (nodal load)	160	lbs
Wards	40	psf
Wards(nodal load)	160	lbs
Corridors (2nd floor)	80	psf
Corridors (2nd floor) nodal load	320	lbs
Corridors (1st floor)	100	psf
Corridors (1st floor) nodal load	400	lbs
Stores	100	psf
Stores (nodal load)	400	lbs

Table 6 Live roof load of hospital building

Code: ASCE-07(Sect. 4.9, page #11)		
$L_r = 20 R_1 R_2$		
R_1	0.6	
R_2	1	
L_r	12	

Material

G-350 material having yield strength of 50 ksi with G-90 coating is used. 1.15 mm thickness is used for ground floor, and 0.09 thick is used for first floor. Deflection should be within the following limits vertical deflection should not exceed $L/360$, where L is the effective span of the member under consideration and while members are loaded with live load as well as dead load the deflection should not exceed the maximum allowable deflection of $L/240$. Horizontal deflection/sway.

1. The horizontal deflection for wall panels shall not exceed $L/120$.
2. The horizontal deflection for main structural frame shall not exceed $H/100$.

Modelling of three storey hospital building

STAAD PRO is used for modelling and analysis of cold form steel building hospital. The principle of matrix stiffness is used in this programme. For assignment of structure elements, the STAAD PRO built-up library of the cold formed standards section has been used. After the structure has been modelled, the restraints have to be given. In case of steel structures, a pin supports are given. The Figs. 7, 8, 9 and 10 show the different views of structural model of hospital.

Analysis and design results

Time history analysis of structure

This is the last step in the analysing of a structure using STAAD. PRO. When the run analysis is executed it shows analysis complete which indicates the termination of analysis process. The Fig. 11 depicts the stress contours of corner stud of ground floor, Fig. 12 Fx graph of corner stud of ground floor and Fig. 12 Fy graph of corner stud of ground floor and Fig. 12 Mz graph of corner stud of ground floor. Furthermore, the Fig. 15 stress contours of member of bracing over window, Fig. 16 Fx graph of member of bracing over window, Fig. 17 Fy graph of member of bracing over window and Fig. 18 Mz graph of member of bracing over window.

Similarly, different components stress and Fx, Fy and Mz graph of member are shown in Fig. 19, 20, 21, 22, 23, 24, 25 and 26, respectively. The graphical results of analysis are shown in the following figures from Figs. 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25 and 26.

Stress contour of beam

Mode shapes

With increase in the number of degrees of freedom of structure, it rapidly turn out to be challenging to evaluate the time

Table 7 Wind load for hospital building

Building classification category	1	
Basic wind speed(V)	100	
Exposure category	C	
Enclosure classification	Enclosed building	
Code	ASCE-07	
$q_h = 0.0256 * k_z * k_{zt} * k_d * (V^2) * I$		
k_z (Velocity pressure exposure coefficient)	1.04	Table 6–3
k_{zt} (Topographic factor)	1	$k_{zt} = (1 + k_1 k_2 k_3)^2$
k_d	0.85	Table 6–4
I	1.15	Table 6–1
Q_h	26.025psf	

Positive internal pressure

S. No	Location	Coefficient	load = $q_h * \text{Coefficient} * \text{spacing}$	Unit
1	Right wall zone	0.38	19.7789696	lb/ft
2	Right roof	0.03	3.1229952	lb/ft
3	Left roof	– 0.61	– 63.5009024	lb/ft
4	Left wall zone	– 0.55	– 28.627456	lb/ft

Negative internal pressure

S. No	Location	Coefficient	load = $q_h * \text{Coefficient} * \text{spacing}$	Unit
1	Right wall zone	0.74	38.5169408	lb/ft
2	Right roof	0.39	40.5989376	lb/ft
3	Left roof	– 0.25	– 26.02496	lb/ft
4	Left wall zone	– 0.19	– 9.8894848	lb/ft

Positive internal moments have more values, hence critical wind in longitudinal direction is applied by STAAD. Pro

history manually. The modes as shown in Figs. 27, 28, 29, 30, 31 and 32 for the mode shapes 1, 2, 3, 4, 5 and 6 of the structure. The analysis of real structures is during nonlinear finite element analysis software.

Design of three storey hospital

The Fig. 33 and 34 show the variation of shear bending and deflection in members. C-lipped section design properties are shown in Fig. 35. Steel design of members is shown in Fig. 36. Design codes. Different design codes used for the hospital are mentioned in Table 9.

Table 8 Earthquake load of hospital building

Z	0.4	(For seismic zone 2A for Madinah as per building code Saudi Arabia Building Code)	
Soil profile type	S _D	Soil profile, Table 4.1, UBC-97	
C _v	0.64	((Seismic coefficient velocity), Table 5.17, UBC-97)	
C _a	0.44	((Seismic coefficient acceleration), Table 5.16, UBC-97)	
R	3	(Inherent over strength or global ductility of structural system), Table 5.13 or 5.15, UBC-97	
N _v	1	(Near source factor), Table 5.19, UBC-97	
C _t	0.035	0.0853 (0.035) for steel moment-resisting frames	
h _n	44.5 feet	Height of top storey	
I	1	Importance factor	
T	0.603 s	Equation (5.30–8), UBC-97	
<i>At roof level (36ft.)</i>			
(1)load of GI sheet	1.126	psf	
(2)Wall cladding and insulation	6.37	psf	
(3)False ceiling	1.723	psf	
Total load at roof level	9.219	psf	
Building area at roof level	5760	sqr. Ft	
DL at roof level	53,101.44	lbs	
<i>At second floor level (24 ft.)</i>			
(1) 20 mm ceramic tile	9.427982	psf	
(2) 10 mm screed	7.911307	psf	
(3) 24 mm cement fibreboard	5.69778	psf	
(4) False ceiling	1.723001	psf	
Total load at second floor level	24.76007	psf	
Building area at second floor level	5400	sqr. Ft	
DL at second floor level	133,704.4	lbs	
<i>At first floor level (12 ft.)</i>			
(1) 20 mm ceramic Tile	9.427982	psf	
(2) 10 mm screed	7.911307	psf	
(3) 24 mm cement fibreboard	5.69778	psf	
(4) False ceiling	1.723001	psf	
Total load at second floor level	24.76007	psf	
Building area at second floor level	5400	sqr. Ft	
DL at second floor level	133,704.4	lbs	
Total dead load of the building	320,510.2	lbs	
V	113,387 lbs	Equation (5.30–4), UBC-97	
V _{min}	15,513 lbs	Equation (5.30–6), UBC-97	
V _{max}	117,520 lbs	Equation (5.30–5), UBC-97	
F _t	4786 psf	Equation (5.30–14), UBC-97	
Level (ft)	Total lateral force (lbs)	Total lateral force per stud (lbs)	
36	32,231.344	350.3	
24	54,103.63858	588.1	
12	27,051.81929	294.1	

Fig. 6 Section properties of C-lipped section

Geometry Property Loading Shear Bending Deflection Design Property Steel Design

Beam no. = 18733. Section: 12CS3.75X135

Length = 11

Physical Properties (Unit: ft)

Ax	0.0182015	Ix	7.67875e-00
Ay	0.0105281	Iy	0.000177213
Az	0.0055875	Iz	0.00262048
D	1	W	0.3125

Assign/Change Property

Material Properties

Elasticity(kip/in ²)	29000	Density(kip/in ³)	0.000283
Poisson	0.3	Alpha	6.5e-006

STEEL

Assign Material

Print Close

Fig. 7 Isometric view of structural model of hospital

Conclusion

- This research aimed at introducing the new material for construction in Saudi Arabia, which is structurally stable

under various loads (mainly seismic loads). The design results have indicated that cold formed steel is secure under various loads. It can be used for the rehabilitation and reconstruction of disaster affected areas in Saudi

Fig. 8 Side elevation view of structural model of hospital

Fig. 9 Front elevation view of structural model of hospital

Fig. 10 Top view of structural model of hospital

Fig. 11 Stress contours of corner stud of ground floor

Fig. 12 F_x graph of corner stud of ground floor

Fig. 13 F_y of corner stud of ground floor

Arabia as cold formed steel structures give the most rapid pace of construction.

- The results also indicated that due to lesser self-weight as compared to any other material, it is more earthquake resistant and is least dangerous for human life even if it collapse.
- The results of the design have shown that cold formed steel can be used for the construction of multi-storied buildings. The material performed very well under various load combinations, thus for the construction of mid-rise buildings can be easily used. The material is especially good for the construction of health facilities, which are supposed to be in working condition at fast rapid construction basis even after disaster.
- For all the structures, which have been constructed, the spacing between the studs is kept 2 feet. The results have proven that they can be increased by increasing the depth and/or thickness of the member. The results

Fig. 14 Mz graph of corner stud of ground floor

Fig. 15 Stress contours of member of bracing over window

show that the number of storeys can be enhanced by using greater depth/thickness of members.

- The development authority must also approve material such as cold formed steel for rehabilitation and recon-

struction for disaster, pandemic affected areas due to its rapid pace of construction.

Fig. 16 Fx graph of member of bracing over window

Fig. 17 Fy graph of member of bracing over window

Fig. 18 Mz graph of bracing over window member

Fig. 19 Stress contours of truss member of bracing over window

Fig. 20 Fx graph of truss member of bracing over window

Fig. 21 Fy graph of truss member of bracing over window

- In conclusion, the cold formed steel is more rapid in construction and earthquake resistant can be the best possible solution for rehabilitation and reconstruction of disaster and pandemic affected areas due to its rapid pace of construction. Moreover, it is favourable for the construction of multi-storey buildings using modern techniques like shear wall. There is a great room for researchers to improve this construction technique.

Fig. 22 Mz graph of truss member of bracing over window

Fig. 23 Stress contours of beam of first floor joist

Fig. 24 Fx graph of beam of first floor joist

Fig. 25 F_y graph of beam of first floor joist

Fig. 26 M_z graph of beam of first floor joist

Fig. 27 Mode 1 shape of structure frequency: 1.782 Hz. Time period: 0.561 s

Fig. 28 Mode 2 shape of structure frequency: 3.464 H. Time period: 0.289 s

Fig. 29 Mode 3 shape of structure frequency: 4.111 Hz. Time period: 0.243 s

Fig. 30 Mode 4 shape of structure frequency: 4.686 Hz. Time period: 0.213 s

Fig. 31 Mode 5 shape of structure frequency: 5.398 Hz. Time period: 0.185 s

Fig. 32 Mode 6 shape of structure frequency: 6.044 Hz. Time Period: 0.165 s

Fig. 33 Variation of shear bending in members

Fig. 34 Deflection in beam member **Fig. 35** Section properties of C-lipped section

Fig. 36 Steel design of members **Table 9** Different design codes used for hospital design

Standards	Description
MBMA	Load combination and wind load estimation (Sect. 1612.3.2)
AISI	Cold formed section design
UBC-97/PBC	Seismic load calculation
ASCE	Live load, live roof load, snow load

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Compliance with ethical standards

Conflict of interest There is not any conflict of interest and ethical issues involved in this research.

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