Static load analysis of inverted umbrella structure for rain water harvesting

Abstract

Thestudy presents a comprehensive structural integrity assessment of inverted umbrella rainwater harvesting systems through an in-depth analysis conducted using the STAAD-PRO software. The inverted umbrella design, increasingly employed for rainwater harvesting in various settings, necessitates a rigorous examination of its structural performance to ensure reliability and safety.The study employs STAAD-PRO environment to evaluate the load-bearing capacities, stress distributions, and deformations exhibited by the inverted umbrella structures. This study contributes to the broader field of structural engineering by establishing a methodology for utilizing STAAD-PRO in the evaluation of unconventional structures such as inverted umbrella rainwater harvesting systems. Different kinds of live and dead loads acting on the structure was estimated and an emphasis is placed on understanding the dynamic interactions between the system components and the forces imposed by environmental factors, including live and dead loads and seismic activities.wind load

The results of the STAAD-PRO analysis offer valuable insights into the structural behavior of the inverted umbrella rainwater harvesting systems under diverse loading conditions. By assessing critical points such as nodes, connections, and supporting elements, the study aims to identify potential vulnerabilities and proposes design modifications to enhance overall structural robustness. Total dead load acting on the structure was found as 2.88kN. The maximum and minimum force experienced by the structure in X, Y and Z direction was found as (2.33kN and 1.37N), (65.12N and 1.37N) and (261.15N and 6.02N) respectively. The structure was also found stable against bending, shear and tensile strength with utility ratio of less than 1. Ultimately, this investigation strives to foster the adoption of reliable and resilient inverted umbrella rainwater harvesting systems, advancing the integration of innovative engineering solutions into sustainable water resource practices.

Keywords: STAAD-Pro, Inverted Umbrella, Rainwater harvesting and Structural design

1. Introduction

Rainfall is a type of precipitation where liquid water descends to the earth's surface. Snowmelt and rainwater are commonly recognized as the planet's main sources of drinking water (White *et al.,* 2007). Due to the high rate of enteric and water-borne disease transmission, inadequate and unsafe water supplies, as well as poor sanitation and hygiene practices, are linked to increased morbidity and mortality. Millions of people worldwide lack access to clean drinking water for home use, and in many developing nations, conventional piped water is nonexistent, unstable, or prohibitively expensive (Chabalala and Mamo, 2001; Liu et al., 2023).

Despite the fact that freshwater covers nearly 70% of the planet, only 2.5 percent of it. The rest is centered in the sea and saltwater. Nevertheless, the majority of our fresh water is frozen in glaciers and snowfields, with only 1% of it being easily accessible. Freshwater reserves on Earth have not changed, but population growth has put the world's water supplies in grave danger (Keskar *et al.,* 2016)

According to (Kim and Yoo, 2009) rainwater harvesting could be one of the most effective ways to restore the natural hydrologic cycle and make urban development sustainable. Rainwater collection may help ease the burden on the nation's storm water drainage systems and existing water supplies. Rainwater collection could benefit a large number of people worldwide.

The process of gathering, transporting, and storing rainwater for later use from comparatively clean surfaces—like a roof, a land surface, or a rock catchment—is known as rainwater harvesting. RWH is a method of gathering rainwater from rooftops, filtering it, and storing it for later use. A straightforward method of collecting and storing rainwater at its source is called rainwater harvesting. Depending on the circumstances, we can either use it to recharge groundwater or store it in tanks for later use. RWH systems are generally more affordable and offer sources of soft, high-quality water, reducing reliance on wells and other sources. Comparatively speaking, building a RWH system is more affordable than building a well, canal, dam, diversion, etc (Jyotiba *et al.*, 2013)

The Inverted Umbrella-Type Rainwater Harvesting System is an innovative approach to collecting and storing rainwater efficiently(Harshitha*et al.,*2020). It is designed in the shape of an inverted umbrella, with a lightweight and durable frame that can be installed on rooftops, open fields, and urban landscapes. This unique design was used with a aim to maximizes rainwater collection efficiency, even during light showers, while occupying minimal space (Tarranum *et al.*, 2023).

High-rise buildings or structures are susceptible to dynamic horizontal loads such as wind and earthquakes. These horizontal forces cause significant stress, displacement and the inherent height of the building causes vibration and ductility, with wind-induced displacement and vibration becoming severe as altitude increases. Rigidity and flexibility have been considered instead of analysis. Structural systems that can be used for lateral resistance of tall structural systems are rigid frame systems and shear walls. Structure in high seismic zones can be susceptible to severe damage. Shear wall act as a key earthquake resistant member in seismic design. Structures are the most popular system to resist lateral loads due to earthquake, wind etc. It is necessary to place the shear wall at an ideal location for effective and efficient performance of the structure (Solanki and Sharma 2022).

2. Materials and Methodology

Raichur is an administrative district in the Indian state of Karnataka. It is located in the northeastern part of the state and is bounded by Yadgir district in the north, Bijapur and Bagalkot district in the northwest, Koppal district in the west, Bellary district in the south, Mahabubnagar district of Telangana and Kurnool district of Andhra Pradesh in the east. The district is bounded by the Krishna River on the north and the Tungabhadra River on the south. The wedge of land between the rivers is known as the Raichur Doab, after the city of Raichur. Bijapur and Yadgir districts lie to the north across the Krishna River. Bagalkot and Koppal districts lie to the west. Across the Tungabhadra lies Bellary District of Karnataka to the southwest and Mahabubnagar of Telangana to the southeast. Kurnool District of Andhra Pradesh state lies to the east and includes the lower portion of the Raichur Doab.

2.1 Structural analysis

The structural analysis for an IU RWH system is vital to ensure the stability and integrity of the system's physical components. It accounts for various loads such as the weight of the structure, the water in the storage tank, wind loads, and other applied loads. Load analysis involves the assessment of forces and stresses acting on the structural components of the IU RWH system. This includes considering the weight of the inverted umbrella, the water in the storage tank, and additional loads such as maintenance personnel. For the structural analysis specialized software like STAAD Pro was used to perform finite element analysis (FEA) and evaluate the structure's ability to withstand forces like compression, tension, and shear. The analysis also takes into account local environmental conditions, like seismic activity and soil types, to ensure the structural design complies with safety regulations and building codes. Detailed engineering drawings and reports are created to document the results of the load analysis and ensure a safe and resilient system design.

2.2 Dead Loads

Self weight of the structure is the summation of self weight of steel pipe, self weight of hallow T-sections, self weight of angle rod and self weight of cladding material

Finally total self weight of the structure is calculated taking additional 10 % of total weight for connections

$$TSW= (W_1+S+SW+SWG) \times 1.1 \qquad \ldots\ldots (1)$$

Where,

TSW= Total self weight of the structure (kN)

W_1 = Self weight of steel pipe (kN)

S = Self weight of T-sections (kN)

SW= Self weight of angle rod (kN)

SWG= Self weight of cladding material (kN)

2.3 Live Loads

As the wind blows against a building or a structure the resulting force acting on the elevations is called the 'wind load'. The building's structural design must absorb wind forces safely and efficiently and transfer them to the foundations in order to avoid structural collapse(Verma *etal.*, 2022)

Design Wind Speed (V,) The basic wind speed (V,) for any site shall be obtained from and shall be modified to include the following effects to get design wind velocity at any height (V) for the chosen structureby Behera (2012):

a) Risk level;

b) Terrain roughness, height and size of structure;

c) Local topography.

It can be mathematically expressed as follows:

$$V = V_b \times k_l \times k_2 \times k_3 \text{ ……… (2)}$$

V_b = design wind speed at any height z in m/s

k_l = probability factor (risk coefficient)

k_2 = terrain, height and structure size factor and

k_3 = topography factor Risk Coefficient

2.4 Structural analysis and design program software (STAAD Pro.)

STAAD.Pro stands for structural analysis and design software developed by Bentley Systems. It is used for analyzing and designing a variety of structures, such as buildings, bridges, and towers. The software offers tools for modeling, load analysis, and compliance with design standards. It has a user-friendly interface, supports international design codes, and is widely used in the engineering and construction industry for ensuring structural stability and safety (Sarath *et al.,* 2020).

2.41Stability analysis:

The stability analysis of an inverted umbrella rainwater harvesting (RWH) system involves assessing its shear, bending, and tensile strengths. Considerations include material properties, shear forces, bending moments, section properties, and tensile loads. It's important to evaluate the structure's ability to withstand hydrostatic pressure from stored water and ensure overall stability against factors like wind loads. Detailed analysis and consultation with a structural engineer are recommended to ensure the structural integrity of the system.

(i) Design compressive strength for steel pipe

The design compressive strength for a steel pipe depends on several factors, including the type of steel, the dimensions of the pipe, and the specific design code or standard being used. Steel pipes are commonly used in structural applications, and their design strength is determined based on engineering principles and relevant standards. Design compressive stress is calculated using the following equation

$$P_d = \frac{f_{cd} \times A}{1000} \qquad \text{... (3)}$$

Where,

f_{c_d} = factor of design compressive strength (Nmm^{-2})

(ii) Bending for steel pipe

Bending in the context of a steel pipe refers to the deformation of the pipe due to the application of a bending moment or force. Bending is a type of structural load that causes the pipe to change its shape from its original straight configuration (Behera, 2012). The design bending strength (M_d) shall be calculated using

$$M_d = \beta_b Z_p f_y \leq 1 \cdot 5 z_e f_y / \gamma_{m_0} \qquad \text{..... (4)}$$

Where,

M_d = design bending strength (kN-m).

$\beta =$ 1 for plastic and compact sections.

$Z_p =$ Plastic section modulii of the cross − section,

f_y = Yield stress of the material ($250 \frac{N}{mm^2}$ for steel)

γ_{m_0} = Partial safety factor for steel (1.10)

3 Results and discussion

Self weight of steel pipe is obtained as 1.09 kN, self weight of steel T section (40 mm x 40 mm x 6 mm) was obtained as 0.52 kN, self weight of angle rod over perimeter (1" x 1" x 1/4") was obtained as 0.26 kN, self weight of cladding material (assumed 3 mm thick) was obtained as 0.74 kN and finally total self weight of the structure (added 10% for connections) was obtained as 2.88 kN. Estimating the self-weight of the steel structure in the structural design of an inverted umbrella rainwater harvesting system is essential for ensuring safety, structural integrity, load distribution, and cost-effectiveness. Proper consideration of the self-weight allows for the creation of a stable, durable, and efficient RWH system that can reliably collect rainwater for its intended purpose while withstanding the test of time.Properly accounting for wind-induced forces in the design process is essential to create a robust and effective rainwater harvesting system that can withstand environmental stresses.

In order to calculate wind load or wind pressure, the design wind speed was calculated and it was obtained as 77.11 ms^{-1} and wind pressure at a height of the structure was calculated using Equation 2 and it was obtained as 3.57 kNm^{-2}.

In STAAD.Pro, analysis of flat members within a 3D structural model for load impacts in the X, Y, and Z directions can be done and also generation of moment diagrams to visualize the load affect on the members is possible. To do this, first creation or importing the model design is necessary then defining supports and constraints, specifying loads, selecting the appropriate analysis type, and running the analysis. After this analysis four distinct figures that show the load impacts on the flat members in the X, Y, and Z directions as well as a moments diagram along the global axis were produced as a result of the STAAD Pro software. Using the colors of the legends it is possible to discern specifics of the load impact.

Table 1: Details of quantum of dead and live loads acting on various components of the developed Inverted Umbrella RWH system.

Sl. No.	Component		Specification	Total
1	Self weight of steel pipe	Outer diameter of steel pipe	0.26 m	1.09 kN
		Inner diameter of steel pipe	0.257 m	
		Thickness of steel pipe	0.005 m	
		Cross sectional area of mild steel pipe	4881 mm^2	
		Height of steel pipe	2.89 m	
		Unit weight of mild steel	7701 kg m^{-3}	0.52kN
2	Self weight of steel T section	Length of type 1 flat (Arc length)	1.63 m	
		size	40 mm x 40 mm x 6 mm	
		Unit mass of T section	3.50 kgm^{-1}	
3	Self weight of angle rod over perimeter	Cross section area of angle	282.26 mm^2	0.26kN
		Unit weight of steel	7701 kgm^{-3}	
		Perimeter	12 m	
4	Self weight of Cladding material	Total surface area of Cladding material	9.80 m^2	0.74kN
		Unit mass	7.74 kg m^{-2}	

5	Added 10% for connections	0.27kN
6	Total self weight of structure (Added 10% for connections)	2.88kN
7	Wind load	77.11 m/s

A 3D STAAD model of the structureis represented in Fig. 1. The maximum and minimum axial compression load in X direction was found as 2.33 kN and 67.14 N respectively (Fig2) likewise the maximum and minimum axial compression load in Y direction was found as 65. 12 N and 1.37 N respectively (Fig3) and the maximum and minimum axial compression load in Z direction was found as 261.15 N and 6.02 N respectively (Fig4).Axial compression and bending checks are done to ensure safety, efficiency, structural integrity, functionality, durability and compliance with structure codes and regulations. Ignoring these factors can lead to structural failures with potentially catastrophic consequences.

Table 2: Load effects on canopy of the structure in X,Y and Z direction

Sl. No.	**Co-ordinates**		**Value**
1	X	Max	2.33 kN
		Min	67.14 N
2	Y	Max	65.12 N
		Min	1.37 N
3	Z	Max	261.15 N
		Min	6.02 N

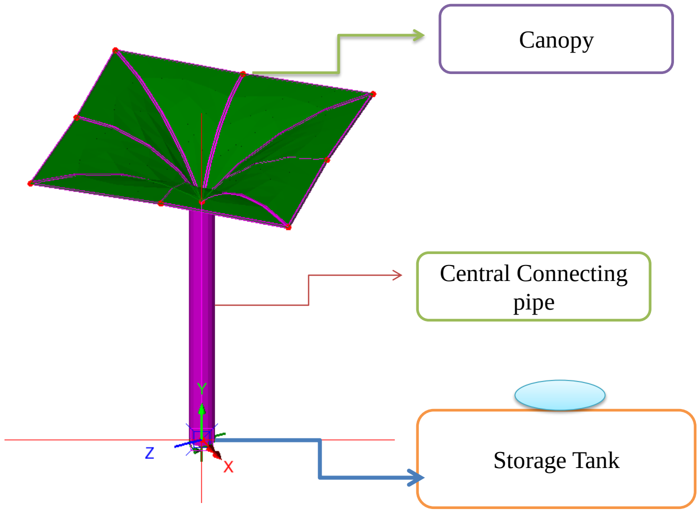
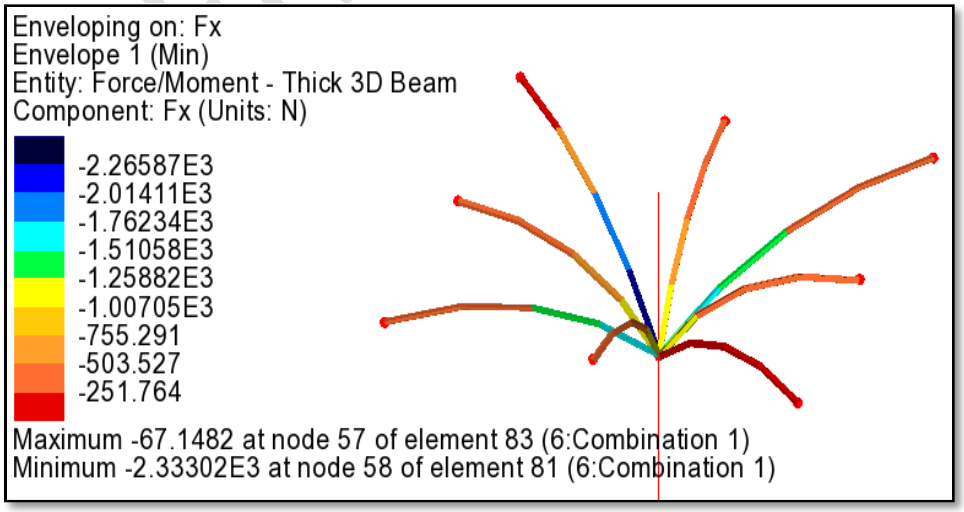


Fig 1: A 3D STAAd Model of proposed structure


Enveloping on: Fx
Envelope 1 (Min)
Entity: Force/Moment - Thick 3D Beam
Component: Fx (Units: N)

Maximum -67.1482 at node 57 of element 83 (6:Combination 1)
Minimum -2.33302E3 at node 58 of element 81 (6:Combination 1)

Fig 2: Load effects on canopy of the structure in X-Direction (Combination 1.5 DL+ 1.5 LL)

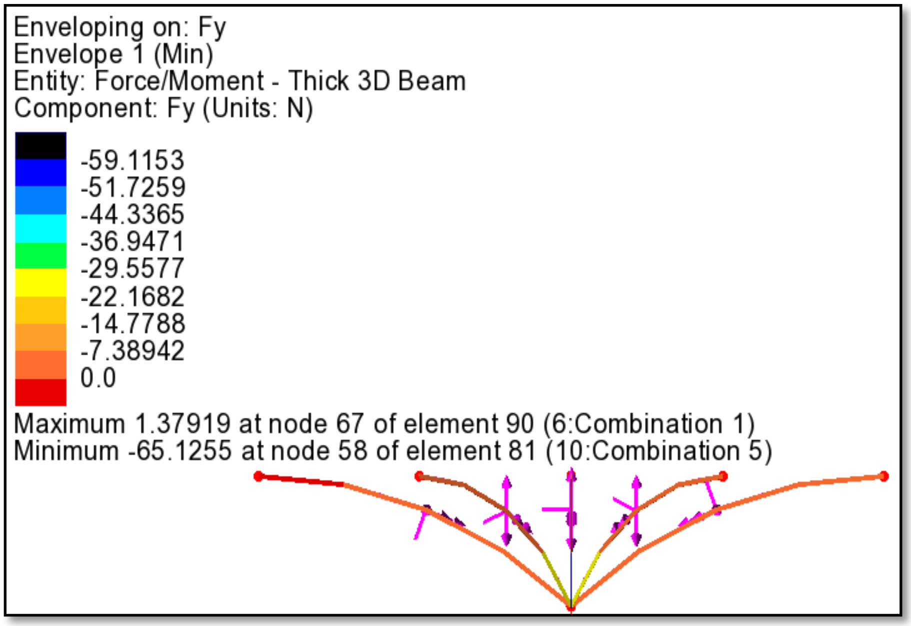


Fig 3: Load effects on canopy of the structure in Y-Direction (Combination 1.5 DL+ 1.5 LL).

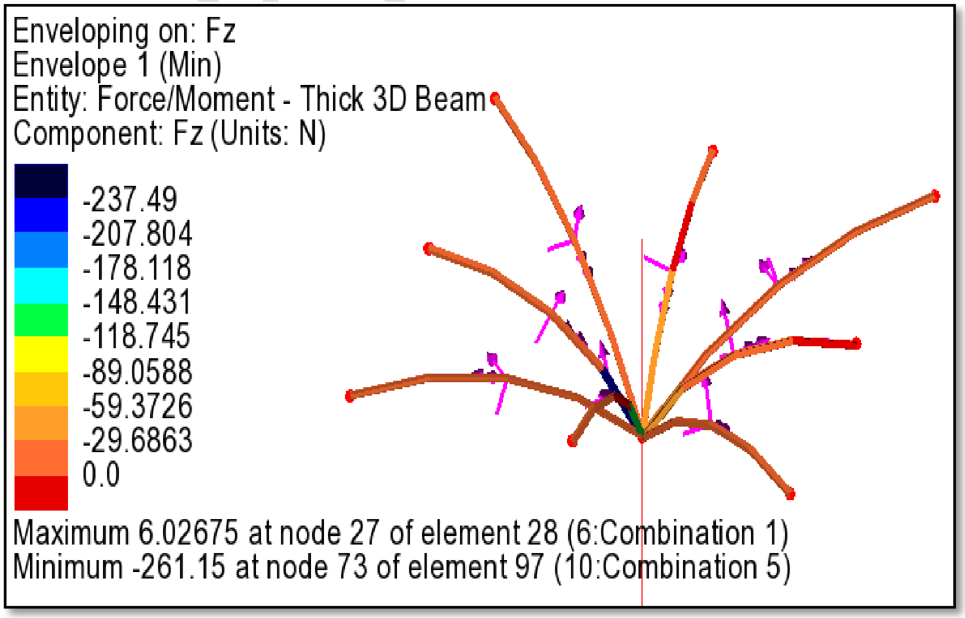


Fig 4: Load effects on canopy of the structure in Z-Direction (Combination 0.9DL+ 1.5WL)

Stability analysis:

Design compressive stress of the developed IU RWH structure is calculated using Equation 3 and found as 941.22 kN(factor of design compressive strength is 192.83 N/mm^2) and utility ratio developed using design compressive stressand maximum compressive force (5.39 kN) of steel pipe was found as 0.001. Utility ratio is found less than 1 therefore the structure is found safe against the compression load applied (Appendix 1). Similar results of utility ratio (less than 1) were also found by Behera (2012), Goyal and Suthar (2022) in order to keep the structure safe against the compression load applied.

The design bending strength (M_d) of the developed structure is calculated using Equation 4 and was found as 93.00 kN-m which was less than $1 \cdot 5 z_e f_y \,/\, \gamma_{m_0}$(107.20 kN-m) and utility ratio was found as 0.29(Appendix 1). As the condition above is satisfying, therefore the structure is safe against bending load applied.Similar results of utility ratio (less than 1) were also found by Behera (2012), Goyal and Suthar (2022) in order to keep the structure safe against the bending load applied.

The structure was again checked for stability against compression, bending and shear forces andthe utility ratio for compression and bending for steel pipe was found as 0.005 and 0.29 which was less than 1, for shear stability check factored Shear force (V) was found as 10.37kN which was less than design shear strength (V_d) 407.74kN.

Table 3: Stability check for steel structure against compression, bending and shear forces in IU RWH system.

Sl. No.	Type of force	Design force (kN)	Maximum force (kN)	Utility Ratio	Stability
1	Compression	Design compressive strength (P_d) - 941.21	Maximum Compressive force - 5.39	$0.005 < 1$	Safe against compression
2	Bending	Design bending strength (M_d) - 93.00	Maximum bending moment- 27.09	$0.29 < 1$	Safe against Bending
3	Shear	Design shear strength (V_d) - 407.74	Factored shear force (V) -10.37	$V \leq V_d$	Safe against Shear

Conclusion:

The Inverted Umbrella-type rainwater harvesting system plays a vital role in sustainable water management, conservation, and resilience to water-related challenges. Its efficient design, combined with proper filtration and treatment, makes it a valuable tool for reducing water consumption, protecting local ecosystems, and also promoting responsible water use in both residential and commercial settings. Since the utility ratio obtained was less the one therefore, the structure was found stable against compression, bending and shear forces acting on it.

The stability analysis of an inverted umbrella type Rainwater Harvesting (RWH) system is essential for ensuring structural integrity, safety, and durability. It helps identify weaknesses, ensures compliance with standards, and contributes to optimal functionality. A stable system reduces the risk of accidents, enhances long-term efficiency, and is cost-effective by preventing future repairs. Additionally, stability analysis supports environmental sustainability, minimizes negative impacts, and positively influences public perception of the RWH system.

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Appendix-1

Load combinations

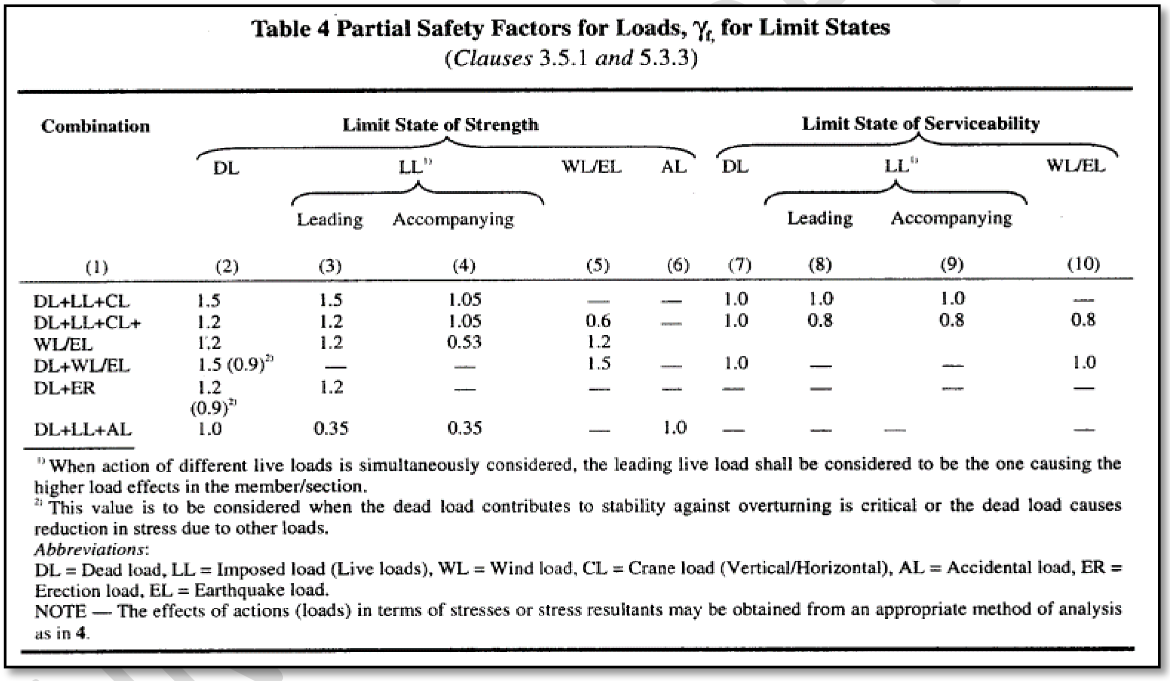

Table 4 Partial Safety Factors for Loads, γ_f, for Limit States

(*Clauses* 3.5.1 *and* 5.3.3)

Combination	Limit State of Strength					Limit State of Serviceability			
	DL	LL[1]		WL/EL	AL	DL	LL[1]		WL/EL
		Leading	Accompanying				Leading	Accompanying	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
DL+LL+CL	1.5	1.5	1.05	—	—	1.0	1.0	1.0	—
DL+LL+CL+	1.2	1.2	1.05	0.6	—	1.0	0.8	0.8	0.8
WL/EL	1.2	1.2	0.53	1.2					
DL+WL/EL	1.5 (0.9)[2]	—	—	1.5	—	1.0	—	—	1.0
DL+ER	1.2 (0.9)[2]	1.2	—	—	—	—	—	—	—
DL+LL+AL	1.0	0.35	0.35	—	1.0	—	—	—	—

[1] When action of different live loads is simultaneously considered, the leading live load shall be considered to be the one causing the higher load effects in the member/section.

[2] This value is to be considered when the dead load contributes to stability against overturning is critical or the dead load causes reduction in stress due to other loads.

Abbreviations:

DL = Dead load, LL = Imposed load (Live loads), WL = Wind load, CL = Crane load (Vertical/Horizontal), AL = Accidental load, ER = Erection load, EL = Earthquake load.

NOTE — The effects of actions (loads) in terms of stresses or stress resultants may be obtained from an appropriate method of analysis as in **4**.