Axial Forces of a Half-spherical Space Truss Structure with Opening

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Abstract – *A half-spherical space truss has a beautiful architectural view that can be applied as a roof on an aesthetic building such as a floating resort, bungalow, etc. For some cases, placing an opening such as a door or window can change the space truss structural configuration. A regular space truss structure has a good stability but changing the structural layout resulting some structural problems. This paper investigated the effect of placing an opening on the maximum axial forces of a half-spherical space truss structure. The result indicated that the gap can increase the axial forces by more than ten times the regular system. Hence, some structural treatments should be conducted to maintain the truss capacity.*

Key Words: *Axial force, Design, Opening, Space-truss*

1. INTRODUCTION

Some architects prefer a half-spherical space truss because of its beautiful view, aerodynamic and easy to assemble the structural system. Truss is famous for its lightweight, effective cost, and easy preparation. It can be applied to large area with a few interior supports. Some references discussed how to design and analyze the space truss structures. A report by H. Klimke and J. Sanchez introduced the design and analysis of the space structure, including the 3D modeling, continuum analogy, structural reliability, and the load carrying behavior [1]. At the same time, other paper discussed about the design of truss structures through reuse [2].

The truss structure is easy to be modified. Various types of truss models have been made. Recent advanced types of the truss structures have developed significantly with a lot of research have discussed their properties and behavior such as the compressive behavior of tetrahedral lattice truss structures [3], mechanical properties of a hierarchical octet-truss structure [4], the nail ductility on the load capacity of a glulam truss structure [5] and also the stability and load capacity of an elasto-plastic pyramidal truss [6]. Structural failure behavior was also discussed by the previous studies as the progressive collapse of space truss structures during earthquake [7], dynamic analysis for progressive failure of truss structures considering inelastic post-buckling cyclic behavior [8], evaluation method for predicting dynamic collapse of double layer latticed space truss structures due to the earthquake motion [9] and also failure and energy absorption characteristics of advanced 3D truss core structures [10].

As a development of recent truss model variation, the present study used a half-spherical space truss. This truss model, next, will be applied as a wall-roof structure on the floating resort bungalow. An ordinary roof structure does not need an opening. As a wall application, there always be an opening, such as a door or window. This opening placement resulted in changes of the truss structural configuration. Irregularity in the structural system can significantly affect the structural capacity, mainly the axial forces. Hence this paper discussed the axial forces of a half-spherical space truss structure with an opening compared to the regular truss.

2. METHODOLOGY

A half-spherical space truss model was chosen. The present analysis used a STAAD.Pro finite element software [11] to arrange the model and find the axial forces of the truss members. Two models were investigated, a regular half-spherical space truss and a half-spherical space truss with an opening. The regular space truss model is shown in **Fig-1**, while the structure with an opening is shown in **Fig-2**. Four main transverse frames were used with an angle between each frame at 45 degrees. In order to find suitable structural integrity and stability, a basic triangular shape was used. This configuration enables the structure to ignore the bending moment contribution, as the truss structure can only resist the axial forces. A total of 33 nodes and 88 truss beam members were made.

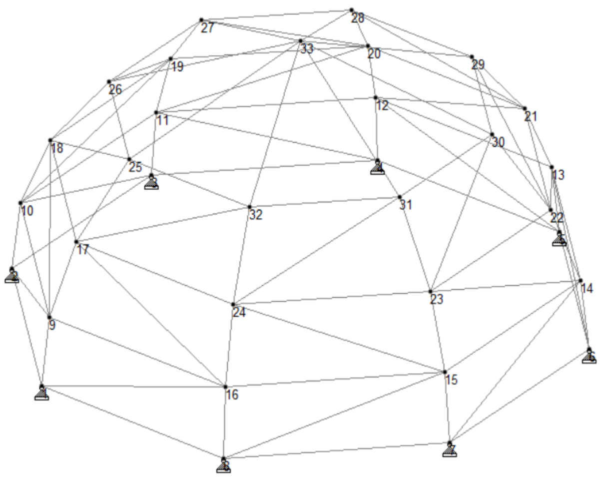


Fig -1: A regular half-spherical truss model

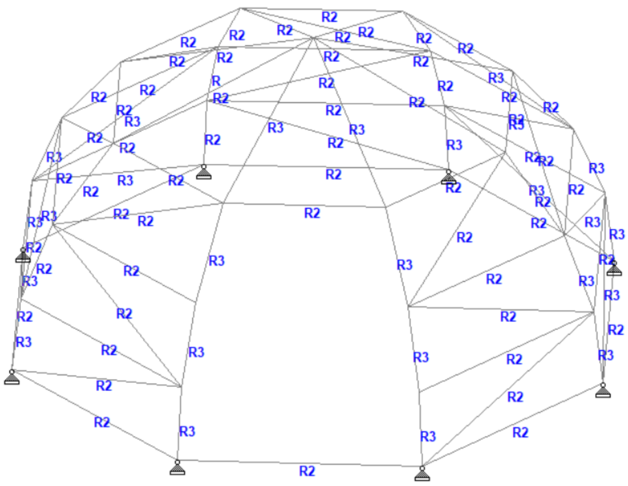


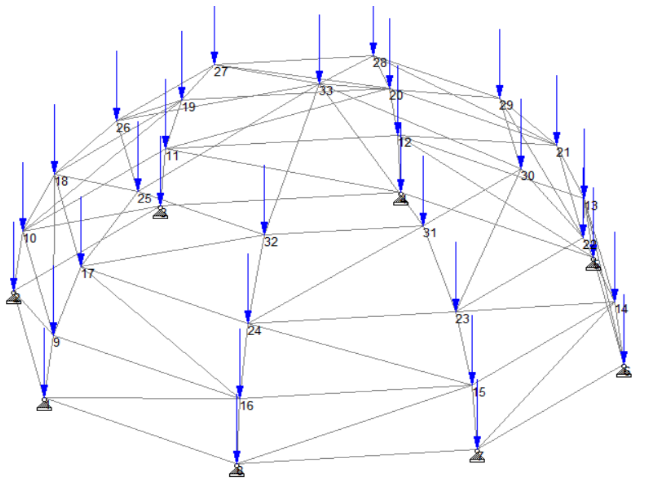
Fig -2: A half-spherical truss model with opening

The truss structure was arranged using a pipe 4/3 SCH40 (USA) steel profile. The material and structural properties of a presently used profile is written in **Table-1**. Each bottom node of the truss structure was supported by pinned support as the truss structure can only carry shear and axial forces.

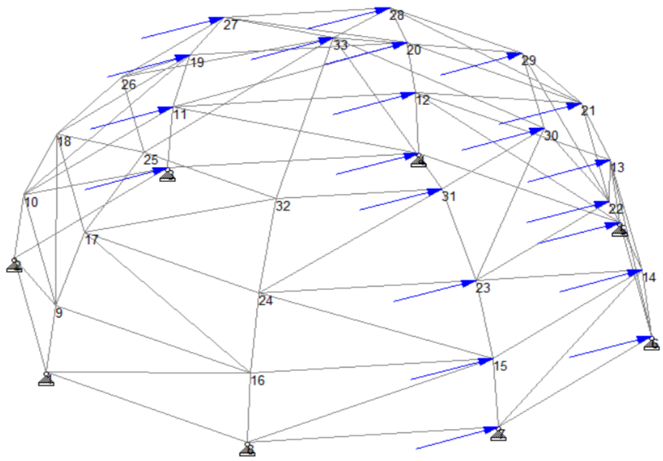
Table -1: Material and structural properties of pipe 4/3 SCH40

Description	Symbol	Magnitude	Unit
Elastic Modulus	E	205000	MPa
Specific gravity	γ	7833	Kg/m^3
Poisson's ratio	φ	0.3	-
Yield stress	f_y	253	MPa
Ultimate stress	f_u	407	MPa
Outside diameter	OD	1.05	inc
Inside diameter	ID	0.94	inc
Area	A	110.918	mm^2
Moment of inertia	I	16649.26	mm^4
Radius of gyration	r	12.251	mm

Three load types, dead load (DL), live load (LL), and wind load (WL), were applied to the structure with the directions shown in **Fig-3**. The dead load was applied using automatic STAAD.Pro menu. The live load was determined according to Indonesian Standard – minimum load for designing building and other structures SNI 1727-2020 [12] as 100 kg applied on each node. Finally, wind load was calculated using the basic load as 25 kg/m^2 (for the non-coastal area), then converted to 21 kg on the half-structure nodes in a horizontal direction.



(a) Live load (LL)



(b) Wind load (WL)

Fig -3: Live and wind loads of truss model

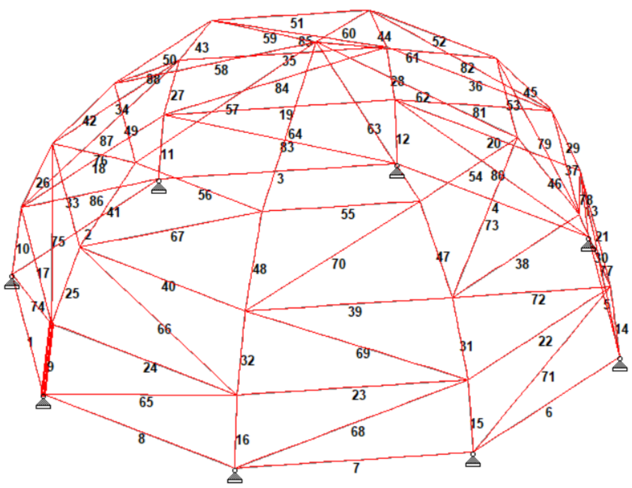
Load combinations were also made according to SNI 1727-2020 as follows:

- 1.2 DL + 1.6 LL
- 1.2 DL + 1.0 LL + 1.0 WL
- 1.2 DL + 1.0 LL + 1.0 WL

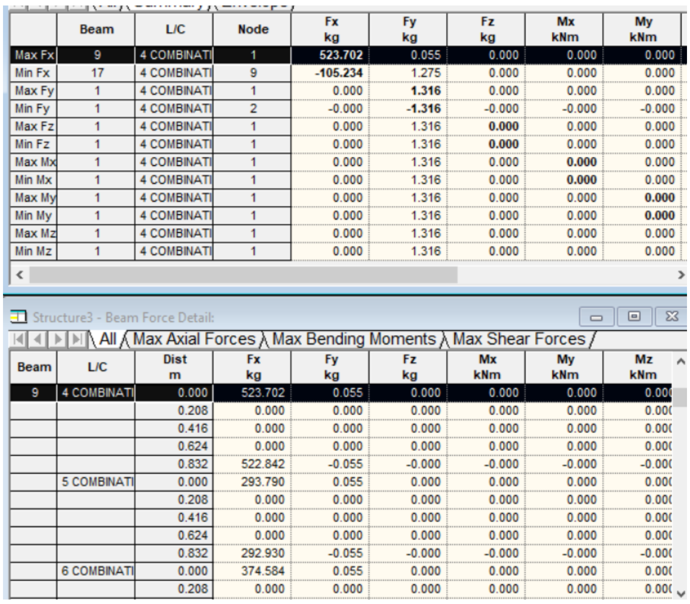
The axial forces output was taken from the maximum value of those three load combinations, which consist of maximum tension and axial compression forces. The result was then compared between the regular structure and the truss structure with opening so that the opening influence on the maximum structural forces could be understandable.

3. RESULT AND DISCUSSION

The result of axial forces from the present regular half-spherical truss system is written in **Fig-4**. Here, the maximum tension axial force of 523.702 kg was found in beam number 9 while the maximum compression force found in beam number 17 was -105.234 kg.



(a) Beam number



	Beam	L/C	Node	Fx kg	Fy kg	Fz kg	Mx kNm	My kNm
Max Fx	9	4 COMBINATI	1	523.702	0.055	0.000	0.000	0.000
Min Fx	17	4 COMBINATI	9	-105.234	1.275	0.000	0.000	0.000
Max Fy	1	4 COMBINATI	1	0.000	1.316	0.000	0.000	0.000
Min Fy	1	4 COMBINATI	2	-0.000	-1.316	-0.000	-0.000	-0.000
Max Fz	1	4 COMBINATI	1	0.000	1.316	0.000	0.000	0.000
Min Fz	1	4 COMBINATI	1	0.000	1.316	0.000	0.000	0.000
Max Mx	1	4 COMBINATI	1	0.000	1.316	0.000	0.000	0.000
Min Mx	1	4 COMBINATI	1	0.000	1.316	0.000	0.000	0.000
Max My	1	4 COMBINATI	1	0.000	1.316	0.000	0.000	0.000
Min My	1	4 COMBINATI	1	0.000	1.316	0.000	0.000	0.000
Max Mz	1	4 COMBINATI	1	0.000	1.316	0.000	0.000	0.000
Min Mz	1	4 COMBINATI	1	0.000	1.316	0.000	0.000	0.000

Structure3 - Beam Force Detail:

All | Max Axial Forces | Max Bending Moments | Max Shear Forces

Beam	L/C	Dist m	Fx kg	Fy kg	Fz kg	Mx kNm	My kNm	Mz kNm
9	4 COMBINATI	0.000	523.702	0.055	0.000	0.000	0.000	0.00
		0.208	0.000	0.000	0.000	0.000	0.000	0.00
		0.416	0.000	0.000	0.000	0.000	0.000	0.00
		0.624	0.000	0.000	0.000	0.000	0.000	0.00
		0.832	522.842	-0.055	-0.000	-0.000	-0.000	-0.00
	5 COMBINATI	0.000	293.790	0.055	0.000	0.000	0.000	0.00
		0.208	0.000	0.000	0.000	0.000	0.000	0.00
		0.416	0.000	0.000	0.000	0.000	0.000	0.00
		0.624	0.000	0.000	0.000	0.000	0.000	0.00
		0.832	292.930	-0.055	-0.000	-0.000	-0.000	-0.00
	6 COMBINATI	0.000	374.584	0.055	0.000	0.000	0.000	0.00
		0.208	0.000	0.000	0.000	0.000	0.000	0.00

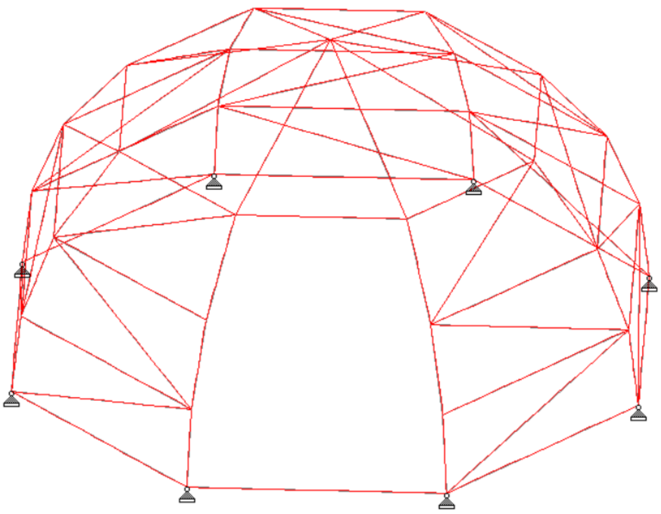
(b) Maximum tension and compression axial forces

Fig -4: Beam axial forces for regular truss

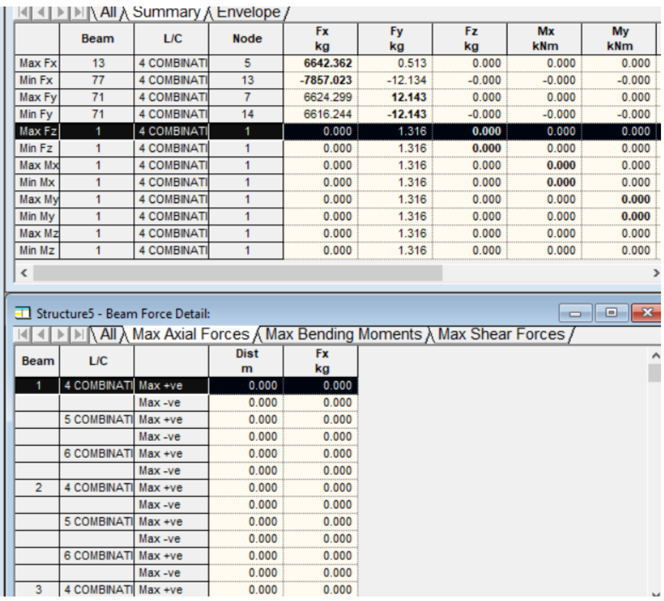
If the used beam steel profile as pipe 4/3 SCH40 (USA) was checked to control the structural capacity, it needs to divide the examination for two types of axial forces which are tension and compression. For tension structural safety examination, the maximum tension axial force from STAAD.Pro software is compared to the maximum allowable structural tension capacity using the yield stress data multiplied by the steel cross-section area. From the data shown in **Table-1**, the maximum allowable force is calculated as 2806.2 kg, which is larger than the maximum tension force as 523.702 kg, which means that the steel profile has fulfilled the safety requirement. For the compression force examination, it is necessary to check the beam slenderness because the structural compression capacity is significantly influenced by the slenderness ratio. The slenderness ratio can be calculated by dividing the beam length and the radius of gyration. From the slenderness calculation as 211.5, the beam is categorized as a slender beam because the beam's slenderness is more significant than 200. The slender beams collapse due to buckling. The buckling load (P_{cr}) can be determined using the Euler equation as follows, where E is the elastic modulus, I is the moment of inertia, and L is the beam length. From the calculation, the beam buckling load of 501.4 kg is larger than the maximum compression axial forces of 105.234 kg which means that the truss also fulfils the safety requirement.

$$P_{cr} = \frac{\pi^2 EI}{L^2}$$

A half-spherical truss system with an opening that was analyzed using similar steps to the regular one. The result of analysis using STAAD.Pro software for the truss with an opening is shown in Fig-5. From this figure, it was found that the maximum tension of 6642.362 kg occurred in beam 71, while the maximum compression axial force of -7857.023 kg occurred in beam 77.



(a) Beam number



All Summary Envelope

	Beam	L/C	Node	Fx kg	Fy kg	Fz kg	Mx kNm	My kNm
Max Fx	13	4 COMBINATI	5	6642.362	0.513	0.000	0.000	0.000
Min Fx	77	4 COMBINATI	13	-7857.023	-12.134	-0.000	-0.000	-0.000
Max Fy	71	4 COMBINATI	7	6624.299	12.143	0.000	0.000	0.000
Min Fy	71	4 COMBINATI	14	6616.244	-12.143	-0.000	-0.000	-0.000
Max Fz	1	4 COMBINATI	1	0.000	1.316	0.000	0.000	0.000
Min Fz	1	4 COMBINATI	1	0.000	1.316	0.000	0.000	0.000
Max Mx	1	4 COMBINATI	1	0.000	1.316	0.000	0.000	0.000
Min Mx	1	4 COMBINATI	1	0.000	1.316	0.000	0.000	0.000
Max My	1	4 COMBINATI	1	0.000	1.316	0.000	0.000	0.000
Min My	1	4 COMBINATI	1	0.000	1.316	0.000	0.000	0.000
Max Mz	1	4 COMBINATI	1	0.000	1.316	0.000	0.000	0.000
Min Mz	1	4 COMBINATI	1	0.000	1.316	0.000	0.000	0.000

Structure5 - Beam Force Detail:

All Max Axial Forces Max Bending Moments Max Shear Forces

Beam	L/C		Dist m	Fx kg
1	4 COMBINATI	Max +ve	0.000	0.000
		Max -ve	0.000	0.000
	5 COMBINATI	Max +ve	0.000	0.000
		Max -ve	0.000	0.000
	6 COMBINATI	Max +ve	0.000	0.000
		Max -ve	0.000	0.000
2	4 COMBINATI	Max +ve	0.000	0.000
		Max -ve	0.000	0.000
	5 COMBINATI	Max +ve	0.000	0.000
		Max -ve	0.000	0.000
	6 COMBINATI	Max +ve	0.000	0.000
		Max -ve	0.000	0.000
3	4 COMBINATI	Max +ve	0.000	0.000

(b) Maximum tension and compression axial forces

Fig -5: Beam axial forces for truss with opening

As it has been calculated for the allowable structural capacity of pipe 4/3 SCH40 steel profile as 2806.2 kg and 501.4 kg for tension and compression forces, respectively, the actual tension and compression forces as 6642.362 kg and -7857.023 kg is much larger, which means that this does not fulfill the safety requirement. For that, it needs to check which beams from the truss system that result in the axial forces more significant than the allowable structural capacity. From the examination, then some beams with over limit axial forces need to be replaced using the more extensive steel profile until the analysis meets the safety requirement. From the investigation, then some beams that have over-axial forces are shown in **Fig-6.** The beams with the red color were then replaced using the larger dimension of the steel profile as pipe 2-1/2 SCH 40. The material and structural properties of this profile are written in **Table-2**. The structural dead load (DL) is automatically adjusted by STAAD.Pro software when steel profile is replaced.

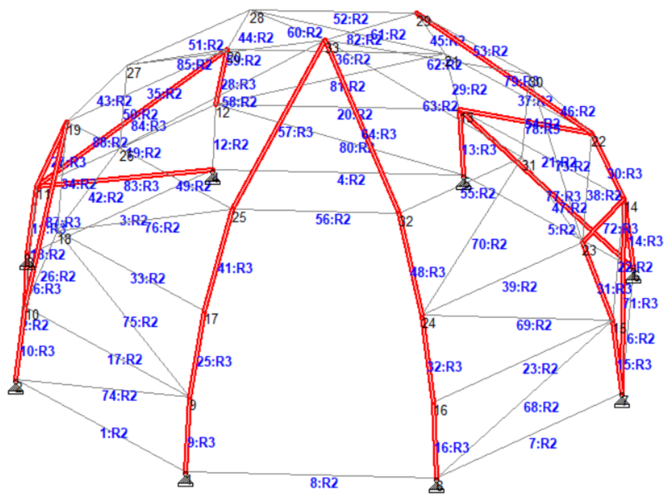


Fig -6: The structural parts that need steel profile replacement

Table -2: Material and structural properties pipe 2-1/2 SCH 40

Description	Symbol	Magnitude	Unit
Elastic Modulus	E	205000	MPa
Specific gravity	γ	7833	Kg/m^3
Poisson's ratio	φ	0.3	-
Yield stress	f_y	253	MPa
Ultimate stress	f_u	407	MPa
Outside diameter	OD	2.88	inc
Inside diameter	ID	2.69	inc
Area	A	536.2485	mm^2
Moment of inertia	I	603535.5671	mm^4
Radius of gyration	r	33.548	mm

Indeed, replacing some of the truss structural parts is difficult to be applied in real fields. But it is very economical because there will be only a slight difference in the maximum axial forces compared to whole steel profile replacement. Using steel profile pipe 2-1/2 SCH 40, the maximum allowable structural capacities as 13567,09 kg (tension) and -18178,11 kg (compression) resulted. If it then is compared to the maximum actual axial forces as 6642.362 kg (tension) and -7857.023 kg (compression), both of them have met the safety requirement. The structural components need to be examined for safety and convenience. For the convenience requirement, structural displacement is needed to be checked against the allowable displacement according to the standard requirement.

4. CONCLUSION

The present study discussed the comparison between a regular half-spherical truss structure and the truss structure with opening to investigate the influence of placing an opening on the space truss system to the structural actual axial forces. Two models were analyzed using STAAD. Pro software. From the results that are mentioned in the previous chapter, it can be concluded that placing the opening resulted in a significant increase in the maximum axial forces. For this case, the increase reached more than ten times compared to a regular truss structure. Therefore, the opening placement disturbs the structural integrity, stability and regularity. To improve the structural capacity, some beam members with large forces should be replaced using the larger profile dimension. If the safety requirement has been fulfilled, then the structures need to be evaluated in the convenience requirement.

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BIOGRAPHIES

Dr. Eng. Lilya Susanti is a teacher and researcher at Civil Engineering Department. She focused on research about the structural mechanics of steel and concrete, structural modeling, and dynamic analysis.