

Progressive Collapse of a Single Layer Schwedler Dome

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Abstract: Large span domes have always drawn architects' and engineers' interest as they provide as easy method of roofing large areas with architectural beauty. Single layer Schwedler Dome composed of Circular Hot Hollow Frame (CHHF) is investigated to understand the effects of individual member removal to the behaviour and stability of single layer dome. The major issues of the structural system are related to its instability phenomena whereby it is vulnerable to snap through buckling. The failure of space structure such as Sultan Zainal Abidin Stadium and Bucharest Dome clearly show an understanding of such failure and the behaviour of the space structure is important to develop a safer structure especially in the future. This study deals with a single layer dome having a diameter of 52 m and the span to depth ratio of $\frac{1}{2}$. The loads subjected on the nodes of the structure consists of dead, live and wind loads and assumed to be 1kN each. Due to the symmetric geometry of the dome, the removals were done on the quarter section of the dome only assumed that the loads distribution patterns are similar for each section. This study required 210 members' removals and the result obtained has been analysed thoroughly. In order to achieve the objectives of the research, computer programming such as FORMIAN, AutoCAD and SAP2000 V18 have been used to generate the geometry of the dome and afterwards analysed the stability of the structure. The numerical technique is based on redistribution of internal loadings due to member's failure. Critical members are determined by analyzing the Demand Capacity Ratio (DCR) value of each member and identifying the number of overstressed neighboring members. When the internal load of a neighboring member exceeds its loading capacity, the member becomes overstressed and fails which may lead to major collapse of the entire structure. The value of the DCR and the numbers of overstressed members existed in the structure after the removals show the criticality of the section. As a conclusion, this critical area must be considered during analysis, design and construction stage of the dome.

Keywords: Progressive collapse, space structures, dome, stability

1. Introduction

Space frame structures can be divided into single-layered, double-layered and also multi-layered structures. As for single-layer steel dome structures, it has been constructed from tubular members and regularly used in moderate span of buildings with spans up to 50 m long such as sport halls and exhibition centres. While for double-layer dome structures have been constructed with clear span slightly greater than 200m. These structures can be constructed either in a flat surface which will resulting in grid structures, or may be curved surface in two or more directions, forming barrel vaults and also dome structures.

In this study, the focus will be on single layer steel dome structure. Dome is one of the examples of space structures that commonly used nowadays. A dome can be separated into two different directions which are horizontal

and vertical section separated by hoops for horizontal section and meridian for vertical section. Like arches, domes also will undergo compression and tension and the stresses will act along the hoops and meridian lines.

However, the structural behaviour of a dome is very complex and it is hard to be predicted especially when the structures are subject to full-service loading. So, in this study, the application of SAP2000 v18 is applied in analysing the behaviour of the structure.

Therefore, because of their highly indeterminate behaviour, an issue would arise since space structure are often assumed to have high degree of redundancy such that the removal of a member would cause redistribution of internal force through the alternate load path after local failure in structures. However, from the previous research related to space trusses conducted by Erling Murtha- Smith [1], the results obtained shows that when the removal of several members is involving the potentially critical members, the progressive collapse of the structure could occur if the structure is subjected to full-service loading. He suggested that the factor of safety of the compression and diagonal members along the column line must be designed higher than the value usually applied in order to improve and increase the resistance of the space trusses against progressive collapse.

From the incident happened in Terengganu, on 2nd June 2009, it had been reported that the whole East Grandstand roof of Stadium Sultan Mizan Zainal Abidin, Kuala Terengganu had collapsed and the royal podium and the main entrance of the stadium are partially damaged due to the impact. From the investigation carried by Arshad et al. [2], the key contributor to the collapse is the removal of number of large diameter members at the critical region in the vicinity of the serious and visible misalignment in the roof space frame structure. This contributes to redistribution of force which resulted in the overloading of certain roof structural members.

The outcome predicted from this research will rebound to the benefit of society especially in providing a safe and comfort facilities and public purposes structure such as sport stadiums, leisure centres, auditoriums and also mosque. Since these structures require a column-free space with longer span, the loads acting on the structure will be transferred along the connected members to the support systems of the building. Once damage or failure occurs on one of the structure members, the loads carried by the member were redistributed which will cause overstressed to the neighbouring members.

Since the stability of the domes is important to ensure the efficiency of the space structure, further understanding about the behaviour of the domes which contributes to member's failure is necessary. This is because, the member damage often happens at the initial stage of progressive collapse of the frame structure. The ability of the structure to tolerate the redistribution loads due to member failure can be identifying by performing alternate path analysis [3].

By using SAP2000 software, the number of neighbouring members affected by the critical members' removal can be identified by analysing their Demand Capacity Ratio (DCR). If the DCR values of all members are less than 1.0, the progressive collapse should not occur but if the values are greater than 1, the possibility of progressive failure is high.

Through this study, progressive collapse due to loss of member in space structure system will be proved. The study also provides a good understanding about the stability of single layer dome and the ultimate purpose of this research is to produce better building evaluation and guidelines to prevent progressive collapse of existing or new building for structural engineers.

2. Collapse of Domes

One of the examples of collapse of domes is National Economy Exhibition Pavilion in Romania which commonly called as Bucharest Dome.

The completion of the overall construction of the dome was in 1961 (see Fig. 1) and it's originally designed as the light weight steel structure. Even though it had received much attention due to its exceptionality of the design, this structure was only last for less than two years which is in 1963 (see Fig. 2). The catastrophe is believed to occur due to unsymmetrical of 2000 kN loading coming from the snow which was surprisingly represented only 30 percent of design load.



Fig. 1 - Bucharest Dome before collapse [4]

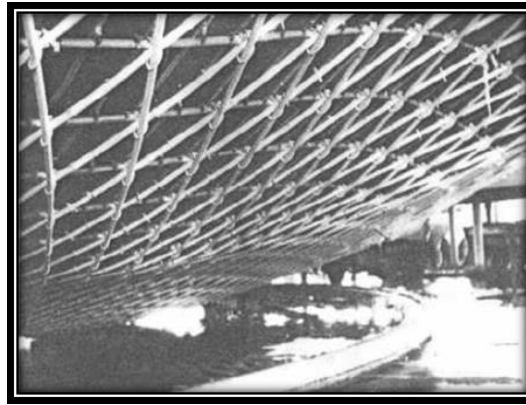


Fig. 2 - Bucharest Dome after collapse [4]

The investigators of the collapse concluded that the main factor contributes to the collapse of the Bucharest Dome is due to non-uniform snow loading which gathered along five radial lines of the structure and the stability of the dome eroded by the poor system of semi-rigid joint applied on the connections. This premature load failure caused the local buckling of the structural members resulted in a perfect inversion of the original structure.

2.1 Vulnerability and Robustness of Dome

According to [5], robustness can be defined as “a structure shall be designed and executed in such a way that it will not damage by events such as explosion, impact, and the consequences of human errors, to an extent disproportionate to the original cause.” Therefore, it can be concluded that robustness of structure is the ability of the structure to resist any action without disproportionate consequences. If it is vulnerable to any unforeseen events such as hurricane wind, earthquake and snow, it cannot be robust. The progressive collapse of De Grolsch Veste Stadium in Enschede (2011), Stadium Southland in New Zealand (2010) and also Sultan Mizan Zainal Abidin Stadium in Terengganu (2009) have clearly highlighted the importance for reducing the structure vulnerability. There are many parameters that influence the vulnerability of structure such as constituent material and also the ductility behaviour of the structure. According to Wenjuan Zhuang [6] from University of Bristol, as long as the structural elements are able to redistribute the energy released and disperse the excess energy, the structure will remain stable and robust. From the research done, they had concluded that the progress of the failure can be obtained from energy distribution. Even the distribution of energy between the members and lower value of structural energy strain density indicates the stronger the structure.

3. Methodology

Numerical analysis by using finite element method is used to analyse the structural behaviour of the dome under loading condition coming from the self-weight of the structure, full-service loading and also lateral loading coming from the wind. The evolution of the finite element software had eased the process to analyse the loads distribution amongst the members of structure and the effects of member removal to the solidity and strength of the steel structure.

As for this study, a simple example of single layer dome with 52 m diameter and span-to-depth ratio of 1/2 having 12 number of rings and 24 number of ribs has been used and the simulation of the complex geometry of the space structure was done by using simple language programming called FORMIAN software [7]. Compared to other software such as AutoCAD and ESTEEM which require a complex and tedious procedure, FORMIAN also can provide an excellent substitute method only by giving a few instructions with simple coding in order to come out with large numbers of members with a complicated geometry. Once the skeleton layout has been modelled, the whole configuration is shifted into finite element software called SAP2000 Version 18 for the design and analysis process.

Fig. 3 shows the editory display for this study as an example on how a numerical model can be generated only by using a simple formulation while Fig. 4 shows the dome configuration based on the formex formulation done.

3.1 Formation of the model

In this case, once the model has been transferred, SAP2000 will design the member sizes and analyse the stability of the dome structure after the removals of the truss members. The design of the dome structure will be done automatically using SAP2000 software with accordance to the Euro Code Standard. Fig. 5 below shows the 3-D view of the single layer dome that has been used for the purpose of achieving the objectives of this study.

Concept of Alternate Load Path Method is applied in this analysis and the static analysis should be adequate since the loss of the members is done gradually. The members of the structure from different area were removed in order to analyse the redistribution of the internal loading of the structure due to members' failure. The critical members will be determined by analysing the Demand Capacity Ratio (DCR) value of the system and the number of overstressed

amongst the neighbouring members. The area having the highest numbers of critical members is assumed as the critical region of the structure. This area will indicate that the stability of the overall structures is at risk if the members from the area are being removed due to buckling and members failure.

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Editory    current file:
(*)Schwedler dome(*)
M=24;(*)No of elements in a ring(*)
N=12;(*)No of elements in a rib(*)
S=52;(*)Span(*)
H=26;(*)Height of dome(*)
A=2*atan(2*H/S);(*)Sweep angle(*)
R=S/(2*sinA);(*)Radius(*)
C=rin(2,M,1)[0,0,0;R,0,1];
E=rinit(M,N,1,1)[[R,0,1;R,1,1],[R,0,1;R,0,2],[R,0,1;R,1,2]];
B=rin(2,M,1)[R,0,N+1;R,1,N+1];
D=C#E#B;
DD=bs(R,360/M,A/(N+1))D;
use &,vm(2),lw(0.6),c(1,35);
clear;
draw DD;|
    
```

Fig. 3 - A generic scheme of the dome

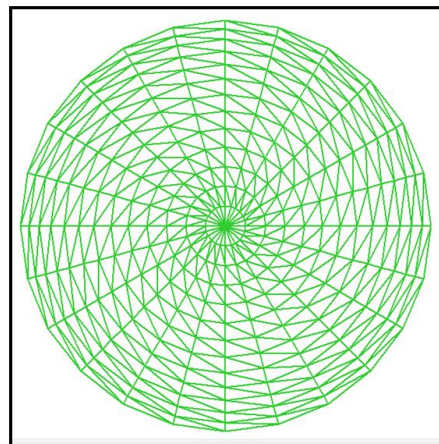


Fig. 4 - A single layer dome configuration by FORMIAN

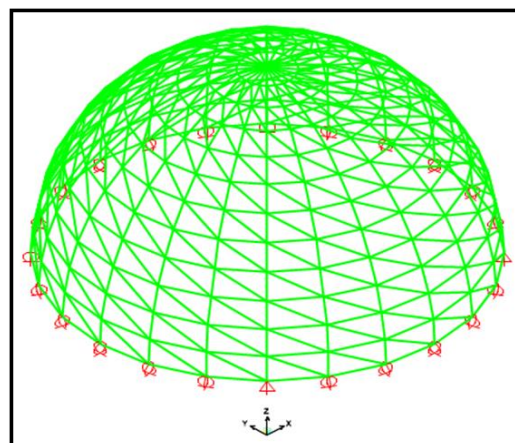


Fig. 5 - 3-D view of single layer dome by SAP2000 V18

Since linear analysis is used for this study, the DCR value of each member can be identified by comparing the member force with the member capacity obtained from the analysis. In this case, during the design stage, the progressive collapse is assumed not going to occur since all the members were designed with DCR value less than one.

However, due to sudden attacks such as explosion, earthquake or abnormal loading, some members of the dome structure may buckle or fail. Therefore, this study focuses on member removal method whereby the members of the dome structures are removed individually and separately assuming that the member is damage or loss due to the sudden catastrophic events mentioned above.

After the member is removed, the loading will have to be redistributed to other nearby members causing some members to be overstressed and have a higher DCR value than the design DCR value during the design stage of the construction. Although the structure is designed with linear elastic behaviour, once the unexpected events occur, the members which having DCR value greater than one will have a possibility to damage and fail which, in turn, will affecting the load path in the structure and cause other members to fail and result in progressive collapse of overall structure.

3.2 Material and Section Properties

The members have been assigned to be Circular Hollow Hot Rolled Sections (CHHSs) and the material having Young's Modulus of 210 GPa, mass density of 7850 kg/m³, Poisson's ratio of 0.3, yield stress of 355 MPa and grade S355 have been selected for all the members based on Eurocode 3 for design of steel structure (BS EN 1993-1-1: 2005).

Besides that, each member of structure used in this study having different length based on the location and the type of members which are column member, beam member and also bracing member. For the beam members, the length was in the range of 0.88 m to 6.79 m while for the bracing members, the length was set from 3.62 m to 7.57 m. As for column members, the length was 3.401 m for all members.

As for this study, the member size and the section properties of the member are automatically selected from the SAP2000 v18 library under 'Auto Section List' mode provided in the software. 'Auto Section List' is the list of the steel section sizes that are available in the database and through this function, SAP2000 v18 has the ability to choose, select and assign the most suitable and economical size and thickness for the members of the structure accordingly.

For economical purpose, the members of the dome should have a minimum weight, size and thickness but still capable enough to resist the loading capacities of the structure. Since this research focused on single layer dome, it is necessary to highlight that the outer diameter for all the circular hollow members must be the same except for the thickness of the member will be varies from each other.

3.3 Loading Conditions

At the initial stage, the structural member of the dome is designed so that the DCR value of each member will be lower than 1 which indicates that the member is safe and strong enough to resist the loadings subjected to the structure. In this study, each of the nodal point of the dome is assumed to be loaded by two negative vertical loads of 1 kN comes from the permanent load and also variable loads. As for the lateral loading, each node is subjected to 1 kN of wind load assuming that the wind direction is at the x-axis.

3.4 Boundary Conditions

In SAP2000 v18 [8], Z axis is indicating the vertical axis while X and Y axes are representing the horizontal axis of the system. In this study, there will be 24 numbers of supports provided by the structure and the boundary condition applied for each of them is different either in translation of vertical Z ($U_z = 0$), horizontal X ($U_x = 0$) or horizontal Y ($U_y = 0$).

3.5 Process of Member Removal

For this study, the total number of the steel members for the single layer dome is 840 members. In order to make the analysis process become easier and faster, the removal of the members is done in the quarter section of the structures only assuming that the load distribution pattern for each section will be the same since the geometry of the dome is symmetrical in X and Y directions. In the process, each members of the quarter section are removed individually and separately so that the significance of the member to the stability of the structure can be analysed. For an example, the first analysis is involving the removal of Member 1 while maintaining the other 209 members of the section. After the removal of the selective member, run analysis is done to show the deformed shape of the structure due to the member removal. In SAP2000, there are two types of analysis that need to be done. The first one is stress/capacity check. For this analysis, the indicator that has been used to check the stability of the steel structure is DCR value of the member. At the first stage of this study, all the members have been set to have DCR value of less than 1 and after the removal, due to redistribution of the loading, some of the members became overstressed with DCR value greater than 1.

After stress/capacity check, analysis and design match need to be performed. Through this analysis, the thickness of the members is automatically assigned by the programme and if the analysis and the design do not match, the system

will run the model repeatedly and it will continue until the programme finds the most suitable thickness for the members and the results show that the analysis and design matches.

Apart from that, it needs to be highlighted that before the Member 1 is removed, all the members are selected and the 'Auto Section List' mode is deactivated. This step is important to ensure that after the removal, the section size and the thickness for all the other members are fixed and the effects of the removal to the redistribution of loads can be defined.

When all the data has been collected, the next analysis is performed by removing another member, which is Member 2 while maintaining all the other members including Member which has been removed in the first analysis. The steps explained above are repeated until all the members in the quarter section have been removed and analysed. The data obtained from the removal of the members are studied and based on the results, the region which having the higher number of critical members can be identified and is assumed as the critical region of the dome which require extra consideration during the design and construction stage of the dome.

3.6 Demand Capacity Ratio (DCR)

The research work is focused on the effects of frame members' removal to stability of a single layer dome and how it can influence to the progressive collapse of the structure. The consideration and the analysis were carried out in linear static analysis by using Finite Element Method (FEM). The dome is designed with a span to depth ratio of 1/2 and the results obtained will be used in identifying the critical region of the structure by evaluating the demand capacity ratio (DCR) of the members and the number of overstressed members due to the removal.

The GSA describes the use of the DCR (Demand Capacity Ratio), the ratio of the member force and the member strength, as a reference to define the failure of main or important structural members by the linear analysis method. Demand Capacity Ratio is very important so that the progressive collapse potential may be reduced up to some extent. If the DCR value of a member exceeds the criteria for acceptance, the member is considered as failed. The DCR values calculated from linear elastic method helps to define the possible potential for progressive collapse of frame structure.

4. Results and discussion

The purpose of this chapter is to show the effects of member removals in a single layer Schwedler dome for the purpose of alleviating progressive collapse of a steel dome structure. This research was expected to come out with a guideline which focuses on the most critical region presented in a single layer dome. This guideline will be applicable and helpful for the engineer during the design stage of single layer dome construction since the criticality of the region has been defined in the guideline. What is more, the stability and the design of the critical region can be put as priority by the engineers. The methodology of this research only emphasizes on one single layer dome and the shape of the dome is symmetrical. Due to the limitation of the research, the removals of the members were selected from a quarter of the dome section considering the distribution pattern of loadings for each section is same. Each node of the structure has been subjected to 1 kN of vertical dead and live load and some nodes were subjected to 1 kN of lateral loading assuming that the wind load comes from one direction only. Since linear static analysis was applied in this research, therefore the Demand Capacity Ratio (DCR) value for each of the members of structure have been analysed after the removal. It is necessary to highlight that during the design stage, all the members of the model were designed with DCR value of less than 1.0 and limitation has been made which at least one member of the structure will have DCR value between 0.90 to 1.0 to ensure that the structure is economical. The assumption used in this study was the member will be considered as critical if the removal resulted in higher numbers of overstressed members existed in the structure. The analysis of DCR value influenced the selection of these critical members and afterwards, the area of the critical region will be defined based on the higher number of critical members presented in the section.

4.1 Analysis of Demand Capacity Ratio (DCR)

In order to achieve the objective of this research as mentioned before, removals of 210 members have been done throughout this study and DCR value of the other members after the removal have been collected and being analysed.

There were 6 meridians involved during the analysis and each of them consists of 12 column members, 12 beam members and 11 bracing members respectively. For the better understanding, the data collected have been categorized into three main groups which are column members, beam members and bracing members. Since the removals of any bracing members did not give any significance which result in existence of overstressed members among the neighbouring members, so the data regarding these bracing members will not be attached and discussed any further in this thesis.

Fig. 6 has graphically shown the comparison on the effects of removing three different types of members on the structural behaviour while Fig. 7 interprets the result in the form of percentage. Based on these graphs, it can be concluded that the removals of column members will lead to higher number of overstressed members compared to removals of beam members and bracing members. This is because, the collapse of a building is initiated when one or more columns which theoretically act as vertical load carrying members is failed or being removed. Once a column is

removed, the gravity load which typically came from the building's weight will be transferred to the neighbouring column of the structure [9] which finally result in greater damage and the collapse of a substantial part of the structure.

The conclusion made by K. A. Giriunas and H. Sezen [9] has been proved through this study. In this present study, there are two section sizes have been used for the members of the structures to fulfil the economic requirement. The column members which connected to the support system have been set by SAP2000 v18 to have a section size of CHHF323.9X10 where all the other members were having a section size of CHHF323.9X5. Based on the results obtained, it clearly shows that when the critical member is removed, the most possible neighbouring members that will become overstressed are among the column members which act as the load transferring members of the structure.

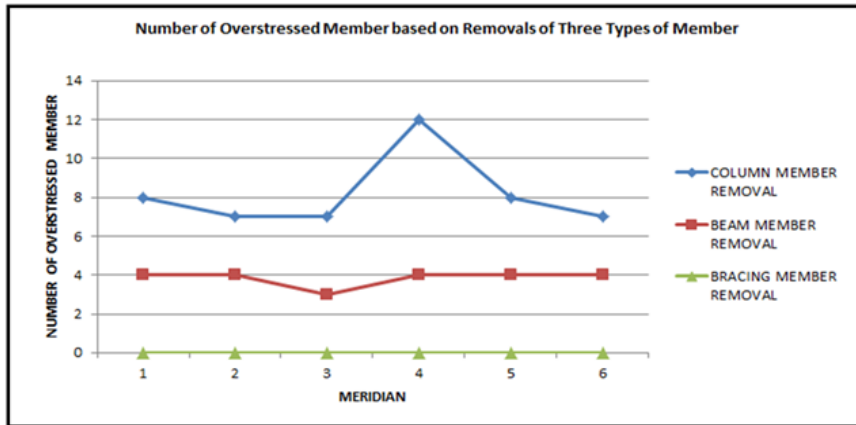


Fig. 6 - Comparison on the number of overstressed member between removals of three types of member

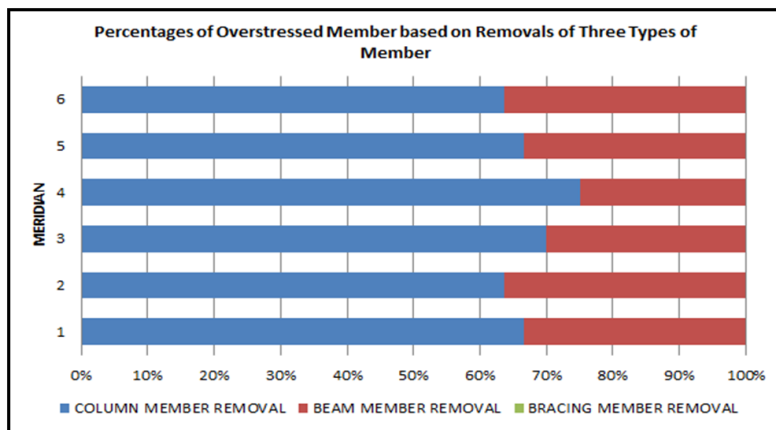


Fig. 7 - Percentage of overstressed member between removals of three types of member

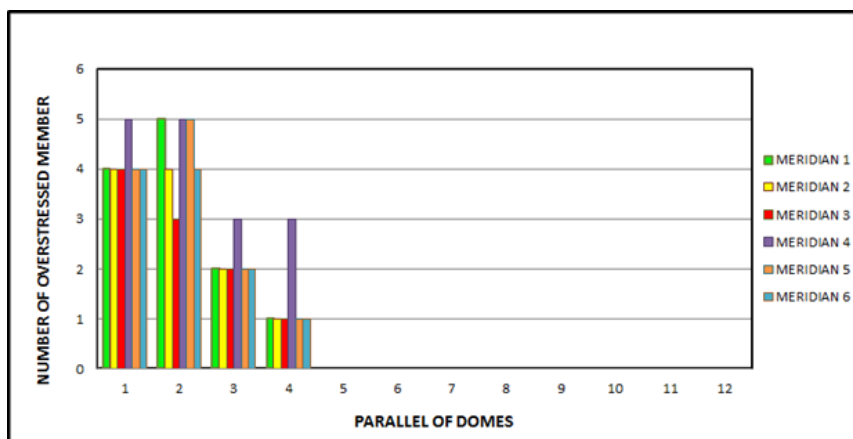


Fig. 8 - Number of overstressed member versus parallels of dome

Based on the graph shown in Fig. 8, it clearly proves that the removals of the members coming from the bottom layer of the dome which are Parallel 1, Parallel 2, Parallel 3 and Parallel 4 will result in the existence of overstressed members in the structure. As the removals take place along the parallels higher than 4, there were no overstressed member and through this outcome, it can be concluded that the critical region of the dome structure is at the bottom part which having the highest number of critical members compared to the other areas.

5. Conclusion

Based on the study, the conclusion is made as follows:

- As the members at the lower part of the dome which is up to Parallel 4 being removed individually and separately, the number of overstressed members existed in the structure was high. However, when the removals were involving the members from the upper part of the structure, there is no member overstressed occurred. From the analysis that has been carried out, it can be said that the critical members of a single layer dome will be existed on the one-third (from below) of the height of the dome. Through this research, it shows that the removals of these critical members will lead the neighbouring column members become overstressed or failed which will result in greater damage on the structure and it will eventually affect the stability and the behaviour of the overall structure. As a conclusion, it is necessary to give extra considerations and contemplations on this critical area during design and construction stage of the dome.
- Column members in single layer dome structure gives clear significance on the stability of the structure since the removal of these members will result in higher number of overstressed members compared to beam and bracing members.
- The removal of the critical members will affect the stability of the overall structure due to the redistribution of the internal loads which will leads to higher number of overstressed members present in the structure. The higher the number of overstressed members produced after the removal, the more critical the member. Based on the data obtained, the most critical member of the dome is member 25 since due to the removal; number of overstressed members is the highest with the DCR value of 1.614 which is 78.343% increment from the original DCR value.

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