Introduction
1.1 The Trend
1.2 Steel as the material
1.3 Truss as the system

Space Frame System
2.1 General Information
2.2 Definition
2.3 Basic Concept
   2.3.1 Single-Layer Grid
   2.3.2 Double-Layer Grid
   2.3.3 Selection of Type
2.4 Advantages
2.5 Preliminary Planning Guidelines
2.6 Proprietary Systems
   2.6.1 Mero
2.7 Bearing Joints

Case Study on Tsim Sha Tsui SOGO Department Store
3.1 General Information
3.2 Design Intention
3.3 Space Frame System
   3.3.1 Double-Layer Grid
   3.3.2 MERO
   3.3.3 Bearing Joint

Conclusion

Reference

Appendix
1 Introduction

1.1 The Trend

Structure is the skeleton of an architecture. Well designed structure could be able to act as a rigid support in all conditions while at the same time, express kinds of technical architectural features. Architects and Engineers are always searching for structures that allow them to achieve larger unobstructed space. Materials, forms, scales, etc, of different structural types were being improved and investigated to obtain a better solution from the past few decades.

With respect to the improving technologies on certain aspects, electronic computing system and invention of new structural materials, more and more structural kinds appear. Application of steel in truss system help to develop a more complete truss system which got a higher strength and durability. Upon the satisfactory performance of such kind of development, steel truss is being more and more popular in the usage of structure. The situation is enhancing architects and engineers to gain experience from actual and practical construction. The system is thus being improved to achieve higher ability and even better performance.

Upon the prevalent use of steel truss system, the objective of this report is to explore the system in a deeper extend, not only framed in the structural aspects, but also covering the architectural considerations, from the case study, Tsim Sha Tsui SOGO Department Store (figure 1a), which is constructed the space frame system as structural support.

1.2 Steel as the material

Steel is a kind of alloy consisting iron, carbon and some other metals for various uses. Nowadays, it is a common construction material as it is produced in a much easier way than the past. Apart from the improvement of production method, it is widely used because of the advantages it has. Steel is ecological friendly with its 100% recyclable property. Also, it would not affected by weather condition that causes warping or twisting, expanding or contracting which affect the structural performance. Concrete requires time for curing but steel is at full strength in all time. And it got properties like higher strength to weight ratio, attractive appearance, capable to be constructed in most conditions, durable but low life cycle cost and good quality control as it is produced in prefabrication.

Considering also the flexibility in form that could be produced, steel is suitable for many kinds of structural systems, in which truss is one of them. Steel has a high ability to resist tension,
1.3 Truss as the system

In structural points of view, it is well-known that triangular units work better than rectangular ones with its rigidity and stability. A truss is a complex structure consisting of triangular elements which are constructed by connection of straight linkage and joints as nodes. In the truss system, nodes are the points that external forces add on. As a result, forces in the straight members would be tension or compression forces.

Applications of truss system in architecture are shown as below (figure 1b & 1c):

![Figure 1b](image1.png) ![Figure 1c](image2.png)

In general, truss can be divided into 2 main categories, planar truss and space frame truss. Planar truss (figure 1d) is composed of triangular elements arranging in 2-dimensional manner which is mostly used in supporting roof as a frame. While Space frame truss (figure 1e) is a frameworks of elements arranging in 3-dimensional manner. The simplest form of element in space frame system is known as the tetrahedron, 4 joints connected to six straight linking members.

![Figure 1d](image3.png) ![Figure 1e](image4.png)

In this report, space frame system would be examined in a more detail extend as the major selected building, Tsim Sha Tsui SOGO Department Store, is constructed with space frame structural roof with certain kinds of features. As mentioned in the above, the exploration would not be framed in structural view points but also in the relationship between the structure, space frame system, and the architecture itself. Advantages and disadvantages of the system would be discovered so as to act as a guidelines for a better selection on the skeleton of an architecture.

On the other hand, two other cases studies would be carried out as a comparison to TST SOGO which all of them are using the same supporting system. Throughout the comparison, it is expected to show the variety of space frame system to be archived, the reasons behind for using it as the main support but not the others and also the spark between architectural concept and technical structure.
2 Space Frame System

2.1 General Information

Due to the improvement in material production and computing technology, complex structures could be invented as the design and construct in such kinds of structure is no longer a dream. Space frame system is one of the benefited structures which allows the architecture to enhance its lightness, economical and fast construction. It is widely used in different kinds of buildings, such as sports arenas, assembly halls, terminals and warehouses with respect to its own visual beauty and structural ability.

Nowadays, construction must be fast and economical. The requirements keep boosting the development of space frame system which is always solving problems of large span with few supporting posts, adverse effect of weather conditions or other similar but difficult problems. It is no doubt that this kind of structure could be applied in many situations with a few disadvantages, so that it is being popular in the world.

2.2 Definition

Space frame is in fact a diversified term that includes many interpretations. It may cause kind of confuse if there is no clear definition to identify which space frame is referring to. With respect to several reference notes and books, it is concluded that a space frame system is a 3-dimensional structure consisting of linear elements and nodes that is able to transfer load in between 3-dimensional arranged elements.\(^1\)

2.3 Basic Concept

2.3.1 Single-Layer Grid

In early stage, space frame system was only a single-layer grid structure. It was a system constructed by the addition of intermediate bracing to the original joist and girder system forming a more rigid connection between components as the single layer grid system. The following figures (figure 2a & 2b) are two different ways to construct roof framing which helps to explain the concept of space frame system. In the roof system of Figure 2a, planar latticed truss system is adopted while the members are bearing the load independently. For the structural stability, purlins and bracing would be added. In Figure 2b, trusses are arranged in space frame grids in which the members are taking the load in an integrated and 3-dimensional manner. As a result, the depth of the system could be decreased with respect to the forces are respectively less in the space frame system.

![Figure 2a & 2b](image-url)
2.3.2 Double-Layer Grid

Load transfer is mainly bending in space frame system, in the cases with requirement of creation in large unobstructed space, it would be suggested to change to double-layer system with a better stiffness in bending and more efficient in the transfer of loads.

Double-layer grids refer to the systems that is formed from 2 planar networks arranging in parallel manner which connect each other by vertical and inclined web members. Generally, it consists of 3 basic components: Planar latticed truss, octahedron and tetrahedron. (figure 2c, 2d & 2e)

With respect to the ways to arrange those basic components, in various direction of the two layers, top and bottom, or to change the position of nodal points in the two layers, many types of double-layer grids could be formed. In accordance with the form of the basic components included in the system, double-layer grids can be separated into 2 main categories, latticed grids and space grids. Latticed grids refer to the system that is formed by two similar grids arranged in parallel intersecting with each other to form a regular grid. While space grids are the systems that composed of tetrahedron or octahedron. Parallel grids with same layout offset from each other in plane but having same directionality.

2.3.3 Selection of Type

Selection of appropriate double-layer grid could help to obtain a more economical but faster construction. There are many aspects that should be taken into account, such as, building layout, supportings, loads, roof types and other requirements stated. Normally, it is more achievable to construct the frame with long tension member and short compression members so as to maintain the structural ability in the system.

Another important factor is the steel expenditure as this would affect the cost of construction in a great extend. In the steel expenditure calculation, it was discovered that the ratio of the span length has a higher influence than the span. Together with the shape of the layout, such expenditure could be investigated while the supporting structure could also be verified.

2.4 Advantages

First and foremost, one essential advantage is its lightness. It is mainly because of the axial load transfer of tension or compression by the spatial distribution of material in a specific manner. As a result, the material composing the whole structure is used in full extend. Also, most likely, the material constructing the space frame is usually steel or aluminium which got lower self-weight. This would be shown in a more considerable extend when the situation requires a longer span.

Secondly, elements in space frame rely on mass industrial production. Prefabrication is always a better choice with respect to its standardization of size and shape which helps to control the quality of each components, especially important for complex system like space frame with many repeating units throughout the whole structure. Prefabricated units can be transported and assembled easily by semi-skilled labour. Eventually, the cost would be lower as the requirements are not that high.
In addition, space frame system is well-known with its stability. With respect to the 3-dimensional arrangement of structural elements and making full use of all material involved, this system is stiff without doubt. It is also appreciated that the system is capable to bear unsymmetrical or heavy concentrated load. The great structural ability thus enhance the flexibility of the whole architectural design in the layout and support positions.

Last but not least, Space frame allows variety of form with repeating standardized units as modular system to create different shapes. The system consists of beauty and simplicity. Structure is no longer a support only, but also the skeleton of the architecture which enhance the visual performance with such a simple and light system.

2.5 Preliminary Planning Guidelines

Firstly, with respect to the complicated elements assemble and geometrical arrangement of units, the most appropriate type of system should be chosen by considering the layout, form and structural conditions so as to match with the requirements.

Secondly, it is also important to consider the geometry of the system as it would affect the structural performance and the total self-loading of the structure. It is closely related to the scale of the building, depth of grid, size of tertiary structure and the supporting positions so that those should be considered in depth to design a suitable space frame for the building.

Thirdly, joint of the system should be designed to match with both structural and aesthetic requirements. In fact, it contributes in an essential manner for the total structural performance of a space frame while composing around 30% of total structural weight, well-designed joint could help to enhance a safe and economical construction. Most likely, joints are selected by considering their complexity, cost, quality and construction ease.

Finally, As mentioned before, an appropriate type of space frame should be selected before detail design as it is closely related to the whole performance. Likewise, the construction method of the selected system should be clearly identified when adopted in the actual site situation and building form. In construction aspect, flaswork should be provided completely so as to allow high position assembling. Or else, provide heavy machine to lift up assembled structure to the right position.

2.6 Proprietary Systems

Upon to the popularity of the space frame system, proprietary systems of certain connection methods are introduced to the construction so as to enhance the construction speed and the accuracy in cost calculation. Such proprietary systems are well-designed units with prefabrication in mass amount, as a result, the cost would be relatively lower while the quality would be in a better control.

The following table shows some common kinds of proprietary systems (figure 2f) :

<table>
<thead>
<tr>
<th>Name</th>
<th>Country</th>
<th>Period of development</th>
<th>Material</th>
<th>Connecting method</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFRO</td>
<td>Germany</td>
<td>1940–1950</td>
<td>Steel, Aluminum</td>
<td>Bolting</td>
</tr>
<tr>
<td>Space Deck</td>
<td>United Kingdom</td>
<td>1950–1960</td>
<td>Steel, Aluminum</td>
<td>Bolting</td>
</tr>
<tr>
<td>Triodetic</td>
<td>Canada</td>
<td>1950–1960</td>
<td>Steel</td>
<td>Bolting</td>
</tr>
<tr>
<td>Unistrut (Moduspan)</td>
<td>United States</td>
<td>1950–1960</td>
<td>Steel</td>
<td>Inserting member ends into hub</td>
</tr>
<tr>
<td>Oktaplatte</td>
<td>Germany</td>
<td>1950–1960</td>
<td>Steel</td>
<td>Bolting</td>
</tr>
<tr>
<td>Unibat</td>
<td>France</td>
<td>1960–1970</td>
<td>Steel</td>
<td>Bolting</td>
</tr>
<tr>
<td>Nodus</td>
<td>United Kingdom</td>
<td>1960–1970</td>
<td>Steel</td>
<td>Bolting and using pins</td>
</tr>
<tr>
<td>NS</td>
<td>Japan</td>
<td>1970–1980</td>
<td>Steel</td>
<td>Bolting</td>
</tr>
</tbody>
</table>

Figure 2f[^4]
2.6.1 Mero

Mero is one type of connectors in the space frame system. It was invented by Dr. Mengeringhausen 50 years ago. Mero is widely used in many buildings. The joint consists of a spherical hot-pressed steel forging with flat facets and tapped holes as the node part while the linkage straight members are with circular hollow sections and cone-shaped steel forgings at the ends for connection use. Bolts are tightened by means of a hexagonal sleeve and dowel pin arrangement and adding up all the components as mentioned, the mero system is completed. (figure 2g, 2h & 2i)
2.7 Bearing Joints

In order to connect to columns or other support for transfer loads, bearing joints are introduced in between the two systems. These joints are specially designed with extra strength for safe transmission of reactions at the support. In general, bearing joints may face different kinds of forces, compression in vertical loading transmission, tension in some double-layer grids while both vertical and horizontal reactions in latticed shells.

Forces and joint positions would be greatly affected by the restraint of the bearing joints. As a result, the construction detail should comply with the restraint as much as possible so as to maintain the force direction throughout the structure.

Hinged joint is used at the point of intersection of other connecting members which could allow free rotation of the joint. Space frame system is fixed in the different directions depending on the temperature conditions. The temperature consideration can be ignored when the support is capable to allow horizontal motion normal to the boundary. In some extreme cases, the bearing support should be taken into deeper caution for large span or complex structures.

The following figures show the typical details of bearing joints (figure 2j, 2k, 2l, 2m) :

![Figure 2j](image1)
![Figure 2k](image2)
![Figure 2l](image3)
![Figure 2m](image4)

1 - MERO node
2 - MERO member
3 - Support cone with bearing
4 - Base Plate
5 - Horizontal stop
6 - Reinforced elastomer
7 - Hook bolt
8 - Compensation grout
3 Case Study on Tsim Sha Tsui SOGO Department Store

3.1 General Information

Tsim Sha Tsui SOGO Department Store (TST SOGO) is owned by New World Development Company Ltd. It was originally designed to be a high class shopping mall, named The Palace Mall, but because of the commercial crisis, the business couldn't run well even in 1998, there was a collaboration with HK Government for a subway construction. From 2002 to 2005, new elements were added to attract pedestrians, New World turned The Palace Mall to the Amazon, with majority of introduction in vegetation and Teddy bears. Finally in 2005, New World rented it to SOGO as TST SOGO.

(Site Location Plan is attached in Appendix 3a)

3.2 Design Intention

With respect to the facade design in TST SOGO, it made use of glazed curtain wall with high transparency, together with glass roof supported by space frame structure which shows a clear design intention to achieve natural sunlight as much as possible. (figure 3a) Considering the surrounding environment, there is no tall and bulky buildings near the site (figure 3b), so that the utilization of transparency as a passive solar design is successful. In fact, such a design could help to introduce favourable natural sunlight to the interior underground parts of the building, while on the other hand, help to lower the energy consumption for artificial lighting.

Figure 3a

Figure 3b
On the other hand, the design of glass box could be an attraction point for pedestrians at night which act as an illuminance showing different colors with light.

Also, there is an architectural featured curve roof on the top. Refer to Figure 3a, it shows that the building surroundings are simple box form, as a result, the architect would like to make some changes not only in the bulkness, but also in the form of the building. The building express kind of lightness with the strategies of transparency and specified curve shape.

3.3 Space Frame System

In order to support the curve glazed roof system, the architect of TST SOGO adopted space frame structure to transfer load from the roof to the columns. Space frame system is an appropriate choice in this situation as the form of roof requires large flexibility in which other systems may do the same but with slower construction and higher cost. Figure 3d shows the curve roof in accordance with the system:

Large unobstructed area is needed to be created. The upper part of TST SOGO is in fact acting as the entrance of the whole shopping mall, the interior space of the upper part mainly for circulation and transmittion of natural sunlight, so that the area should be unobstructed to maintain the lightness achieved. With its own structural ability, space frame system can obtain large span as required without making the roof and beam to be bulky or heavy but express kind of visual beauty with its simple and linear combination of units. The supporting system is shown in Figure 3d as below:

Construction cost could also be decreased while construction speed could be increased. Space frame system make use of modular units of components. In TST SOGO, it make use of double-layer grid with nodes and straight members arranged in 3-dimensional manner, enhancing the rigidity and those units are produced by prefabrication in which the quality would be up to standard and the cost could be lower with mass production and only required semi-skilled labours.
3.3.1 Double-Layer Grid

As mentioned, it is required to leave a large space without obstruction in the interior part of the TST SOGO. In order to achieve such requirement, the space frame system should be well-designed and chosen in which its stiffness should be up to certain levels. While double-layer grid space frame systems are mostly having greater strength than single-layer ones. In addition to the featured curve roof, which increase the forces that the system need to resist in more direction, so that the following double-layer grid system is selected to transfer the load to the side columns. (see figure 3e)

![Figure 3e]

3.3.2 MERO

Again, with respect to the curve roof design, the supporting system is required to be flexible so as to maintain the stability of the entire roof system. MERO units of components are selected to participate in the space frame system with its flexible direction of connection over the spherical node. As a result, certain amount of degree could be twisted along the supporting frame whereas to follow the curved roof and no unwanted load to be taken for enlarge of supporting frame or other problems. (see figure 3f, 3g & 3h)

![Figure 3f]

![Figure 3g]

![Figure 3h]
3.3.3 Bearing Joint

In TST SOGO, there are columns to support the space frame system for transferring of loads. So as to transfer load at the joint successfully and safe, the bearing joint is selected in a more appropriate manner. (see figure 3i)

The joint is located next to the column in order to transfer load in horizontal direction. It should be related to the shape of the layout and the types of grids selected. Together with the possible effect of temperature conditions, it was designed to joint the MERU units to the column horizontally as shown in Figure 3i.
Conclusion

In conclusion, the introduction of space frame system to architecture helps to solve myraids of problems in various situations. There are many merits for the use of space frame, such as, lightness, stiffness, cost effective and standardized quality control. As a result, the use of space frame is being more and more popular with proprietary products to improve the convenience and flexibilty in space frame design. Space frame is not only a well behavior supporting system, but also express simplicity and visual impact with respect to its linear repeating components. Structure is no longer a structure but become a part of an architecture.

In Tsim Sha Tsui SOGO Department Store as the case study of space frame system, it shows many merits of the system in practical adaptation. The repeating MERO units allow flexibility in curve roof design while maintaining the stiffness and unobstructed area in the interior space, so that the design concept of “transparency” and introduction of natural sunlight could be achieved without expensive construction cost or complex construction method.

Indeed, the design consideration is no longer framed by shapes or forms as space frame system helps to construct creative forms with lightweight support. What should be concerned would be the planning before construction, that is the preliminary design stage, which may cause structural failure if the selection of grid types or the joints were not appropriate. Also the construction method should also be well-thought in order to archieve rapid construction to lower the construction cost. The merits of space frame are obvious, which is only depending on how integrate we can make use of the system.

Reference

Handbook of Structural Engineering - Tien T. Lan
[1] - Chapter 24, 24.1.2 Definition of Space Frame
[2] - Chapter 24, 24.1.3 Basic Concept
[3] - Chapter 24, 24.2.1 Types and Geometry
[4] - Chapter 24, 24.5.2 Table 24.9 Commonly Used Proprietary Systems
[5] - Chapter 24, 24.5.2.1 Mero
[6] - Chapter 24, 24.5.3 Bearing Joints

The Structural Basis of Architecture - Sandaker and Eggen

Wikipedia
Appendix

6.1 - 3A Site Location Plan

6.2 - Common Types of Proprietary Products

Handbook of Structural Engineering
Chapter 24, 24.5.2
Commonly Used Proprietary Systems