A Review of the Development of Spatial Structures in China

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ABSTRACT

The development of contemporary spatial structures for long-span roofs in China was initiated in the 1950s. Space trusses, reticulated shells and cable suspended structures have been developing rapidly since 1980s. Recently there has been a growing interest in tensile membrane structures. Comprehensive theoretical study has been carried out parallel to the engineering application, which provided necessary theoretical support to the development of different types of spatial structures.

1. Introduction

All the structures in the practical three-dimensional world are essentially of spatial character. Only for the purpose of simplification of construction and analysis most of the structures are designed as assembled of a serious of plane systems, parallelly and jointly bearing the loads. Meanwhile, spatial structures in their real sense, which cannot be divided into plane systems have been developing rapidly, especially for long-span (or large-space) constructions, demonstrating their colorful forms of application, excellent three-dimensional behavior of resisting external actions and great potential of further development.

Although China has a long history of application of suspended, arched and domed structures for bridges, residences and underground tombs which can be traced back to ancient time, the development of contemporary spatial structures for long-span roofs was initiated only in the 1950s.

The reinforced concrete shells can be indicated as the earliest application of spatial structures in roofs. During the 1950s extensive theoretical and experimental research was carried out on different types of shells. Several reinforced concrete shells of medium scale were constructed during that time, including domes, double-curvature shallow shells and cylindrical shells. Most of the shells were constructed with cast-in-situ concrete, which needed a considerable amount of formwork and scaffolding, as well as rather heavy labor work. Due to the difficulty encountered in construction, reinforced concrete shells are used to a very limited extent nowadays in China.

Cable suspended structure as an effective system for long-span roofs was studied and constructed in China as early as in late 1950s. The suspended roofs of Beijing Workers' Sports Hall and Zhejiang People's Gymnasium in Hangzhou are two representative examples of outstanding engineering projects at that time. The dimensions of these two structures are quite large, comparable to those of similar structures in the world at that time. After a standstill of near 15 years, cable roof structures have obtained its new development since early 1980s. Quite a few sports buildings have been constructed with cable suspended structures of different types: single-layer cable system, counter-stressed double-layer cable system, single-layer cable system with transversely stiffening trusses, cable net of saddle shape and more complex systems of combined or hybrid form.

Probably the latticed space structure is the kind of most widely used spatial structure in China. The term "latticed space structures" is defined as a structural system assembled of linear elements arranged in a three-dimensional manner, and is usually used in China to cover both plate-like space truss and reticulated shell. In some literature it's also named as "space frame". Since the construction of the first reticulated dome in 1954 and the first plate-like space truss in 1964, the technology in design and construction of latticed space structures in China has experienced a great progress. Nowadays, these structures could be applied for various types of buildings from short to long span. Problems encountered in the design of space truss and reticulated shell have been studied to a large extent. The specifications for design and construction of space truss was promulgated in 1991 ; the specifications for reticulated shells, as well as for cable suspended structures, have been completed and are now under examination for approval.

Recently there has been a growing interest in tensile membrane structures. Although there are only few significant projects constructed with membranes yet, engineering proposals and designs have been warmly discussed for quite a few planned projects, and attention of many researchers has been attracted to the corresponding theoretical studies. It's expected that such type of innovative structure would enter a stage of deserved development.

2. Wide Spread Application of Latticed Space Structures

Reticulated shells were used earlier than space trusses. The steel reticulated dome with a span of 46.32m constructed in 1954 for the Zhongqing People's Hall is usually considered as the first latticed shell of modern type in China. There were constructed in the 1950s and early 1960s several steel domes of rib-ring type or Schwedler type and several cylindrical vaults with rhombic net system assembled of steel or reinforced concrete members. However, the reticulated shells did not get further development until the beginning of 1980s.

Relatively, the space truss has been keeping a continuous development since its first application in China in 1964 for constructing a school gymnasium in Shanghai. The Capital Sports Hall completed in 1968 and the Shanghai Sports Arena completed in 1973 were two representative examples of the earliest large-space constructions with application of space truss [1]. The Capital Sports Hall adopted two-way diagonal lattice grids, measuring 99×112m and with a depth of 6m, built with angle sections and connected by high tensile bolts with a steel consumption equal to 65kg/m^2. The Shanghai Sports Arena with a circular plan is 110m in diameter and projected 7.5m from the peripheral supporting columns. Thus the space truss with three-way lattice grids is 125m in total size and 6m in depth, which was built with steel circular tubes connected by welded hollow spherical nodes with a steel consumption equal to 47kg/m^2. At that time in China the space truss was considered as a very novel and innovative type of structure. The successful construction of these two big space trusses made strong impression on engineers and researchers. Encouraged by the sustained demand of construction of gymnasiums, research and design institutions paid much attention to the study of this new type of structure, and special manufacture/construction enterprises were established and developed, and thus a rather solid foundation for the further development of this structure was gradually established. Bolted spherical joint was developed and became popular in practice, which made the assembly of space truss much simplified. Special CAD programs were improved, and the design of space truss became no more difficult.

Different methods of erection of space trusses have been developed. Parallel to the traditional method as named as "assembly in the elevated position" which seems less efficient and requires a considerable amount of scaffolding, innovative methods such as "sliding method", "lift by blocks method", "bodily lift method", etc. have been applied in practice. The space truss of Shanghai Sports Arena was assembled on the ground and then lifted by 6 derrick masts of 50m high, using 12 electric winches as the driving device. The space truss was lifted to a level O.5m above the top of the pre-erected columns and then slightly rotated horizontally to rest directly on the column tops. The Shenzhen Gymnasium adopted a space truss with a total Size of 90×90m supported on four columns with an inner span of 63m. The whole roof structure was assembled on the ground and then jacked up by eight hydraulic jacks mounted on the columns. It is economical to make use of the load-bearing columns of the building as the supports for lifting the space truss, thus avoiding the erection of heavy hoisting masts. The sliding technique was employed during the erection of space truss for Zhenjiang Sports Hall, Jiangsu Province and some other space trusses of medium span. Separate strips of the space grids could be assembled on ground and then hoisted to one end of the roof. They also might be assembled on a platform at the end. The strips were put on sliding rails, towed by some driving devices one after another to their final positions and connected together to form the complete structure.

The fields of application of space truss have been greatly expanded. A noticeable trend of application of such structure is perhaps for the construction of airplane maintenance hangars and industrial buildings. The maintenance hangar requires large inner space and has one of the longer sides opened for the door, besides, the roof should provide supports for the suspended cranes and other equipment. The space truss supported on three sides and with a powerful edge girder along the free side is then considered as a rational solution for the roof structure. The hangar of Beijing Nanyuan Airport with a plan of 54×48m was an earliest example of such a structural solution. Recently the space truss has been satisfactorily applied to cover hangars with larger spans, such as the hangar at Guangzhou Baiyun Airport(80×54m), the hangar of Chengdu Airplane Maintenance Works (140 X 80m), the new hangar at Beijing Capital Airport (2×153×90m)[2], etc. Because of the heavy load and the special supporting condition the space trusses for hangars usually adopt welded two- or three-layer grids assembled of rather heavy steel sections, and the steel consumption is much higher than the space trusses used in public buildings.

One of the most Important fields of application of the space truss is in single-storey industrial buildings. The space truss allows large column spacing which creates maximum flexibility in production. The processing factory of the Tianjing Steel Tubing Mill employs continuous space truss supported on a column grid of 36m by 18m. The total area of the factory amounts to 6000Om^2. The space truss is assembled of circular tube members connected by bolted spherical joints with a steel consumption of $32kg/m^2$. Compared with conventional plane trusses, the application of space truss leads to a substantial saving of steel by 47%. Recently, in the First Automobile Works in Changchun, a huge assembly plant for Golf sedans has been completed with space truss supported on a column grid of 21×12m and with a steel consumption equal to $31kg/m^2$. The dimensions of the plant are 421.6m by 189.4m, covering a total area of $80000m^2$, which is believed to be one of the largest space truss roof structures in the world.

With the advance of large-scale construction in China since early 1980s, it was strongly felt that the space truss as the only selection of long-span spatial structures at that time could no more meet the increasing demands on constructions with different service functions and varied architectural shapes. The other types of spatial structures such as reticulated shells and cable-suspended structures were then to be studied and applied again. Owing to the new production condition established with the development of space truss, the reticulated shells have been developing rapidly since late 1980s. Different types of reticulated domes, cylindrical vaults, double-curvature shallow shells and saddle shells of hyperbolic paraboloid type have been erected. The reticulated cylindrical vaults were erected no more from concrete. The double-layer reticulated vault with a plan of 58× 135m (span by length) for a urea storehouse in Henan Province and a similar one with a plan of 103.5×80m for a coal bunker in Zhejiang Province were two typical examples during this period. These structures adopted orthogonal square-pyramid net system assembled of circular tube members connected by bolted ball joints.

Single-layer reticulated domes have been mostly used with plan diameter less than 50m, usually constructed from circular tube members connected by welded hollow ball joints. Bolted ball joint possesses advantage of simplifying erection, but behaves more likely as a hinge and seems unsatisfactory for single-layer domes from the viewpoint of overall stability of the dome. So some kind of prefabricated joint of embedded-hub type, which is expected to be able to provide with necessary bending rigidity in the direction normal to the shell surface, has been developed. This joint has been applied in several single-layer domes and seems successful. For more large domes, say, with plan diameter over 60m double-layer systems were mostly adopted. For example, the Panzhihua Sports Hall in Sichuan Province, having an octagonal plan with diagonal dimension of 65m, employed a double-layer reticulated dome of geodesic system assembled of lattice elements with a depth of 2.2m. In order to increase the rigidity of the structure, this dome was pre-stressed by a set of high-strength cables, fixed between certain selected points of the dome.

Reticulated shells of negative Gaussion curvature have also been getting applications, mostly used in some combined way to form certain novel architectural shapes. Two gymnasiums built for the 1990 Beijing Asian Games were well known as the typical examples of such kind of reticulated shells. The gymnasium of Beijing Institute of Physical Education with a square plan of 59.2× 59.2m was composed of four double-layer reticulated shells of hyperbolic paraboloid (HP) type with a depth of 2.9m. The Shijingshan Gymnasium triangular in plan with a side length of 99.7m was composed of three quadric-lateral double-layer reticulated shells of HP type with a depth of 1.5m, supported on a trifurcate central frame and reinforced concrete perimeter beams. Meanwhile, the Deyang Gymnasium in Sichuan Province built in 1995 employed a single double-layer reticulated shell of HP type with a square plan of 75×75m and a depth equal to 2.6m.

Recently several reticulated shells of relatively large dimensions have been constructed. The new Tianjin Gymnasium with a circular plan of D=108m and rise equal to 15.4m employed a double-layer reticulated dome of Schwedler system with a depth of 3m assembled of circular tube members connected by welded hollow ball joints. A reticulated shell to cover a 400-meter speed-skating track has been built for the 1996 Winter Asian Games held in Harbin [3]. The shell was combined from a central vault and two half-domes at both ends to form a pseudo-elliptical plan with overall dimensions of 86.2× 191.2m. The square-pyramid and triangular-pyramid net systems were adopted for this double-layer reticulated shell with a depth of 2.1m assembled of circular tube members connected by bolted ball joints with a steel consumption of 50 kg/m^2. A reticulated shell for Changchun Gymnasium was completed in 1997, which was composed of two segments of dome to form a quasi-elliptical plan with overall dimensions of 146 ×191.7m (net space 120×140.7m)[4]. The double-layer shell adopted Schwedler net system for the segments of dome and was assembled of lattice elements with a depth of 2.8m built with rectangular tube members connected by welding. It is the first reticulated shell to use the rectangular steel tube sections in China. More recently, five double-layer reticulated domes with plan diameter equal to 120m using circular tubes and bolted ball joints have been constructed for coal bunkers in Xiamen (Amoy), Fujian Province. These structures as described above seem to be the largest reticulated shells in China at present. With the rapidly increasing amount of constructions with space trusses and reticulated shells, it seems important to strengthen the management of enterprises, as well as the technical guidance in design and construction practice. For this purpose, the "Specifications for Design and Construction of Space Trusses" and the "Standards for Quality Inspection and Assessment of Space Trusses" were promulgated in 1991. In addition, the "Technical Specifications for Reticulated Shells" has been compiled and is now under inspection for approval.

3. Development of Tensile Structures

The circular roof of the Beijing Workers' Sports Hall built in 1959 with a diameter of 94m adopted double-layer cable suspended structure of bicycle-wheel type, and the Zhijiang People's Gymnasium built in 1967 employed pre-stressed cable net of HP type with a elliptical plan with major and minor axes equal to 80m and 60m, respectively[1]. These two outstanding engineering projects were the only examples of the earliest application of cable suspended structures in China. They have been working satisfactorily through these years and are now still in good condition.

Since early 1980s the Chinese engineers have made efforts to develop different forms of application of cable-suspended structures. In Shandong Province quite a few public buildings of middle span have been built with suspended roofs. They usually employed single-layer cable system, on which pre-cast concrete slabs were hanging. The cables were pre-stressed by over-loading, and the seams between the slabs were then filled with fine-aggregate concrete. After unloading, the cables and concrete slabs act integrally, forming a pre-stressed "suspended shell". Such construction does not require any sophisticated technique and is very economical in comparison with other type of roof structures. A double-layer counter-stressed cable system was applied in Jilin Ice-skating Rink completed in 1986 with a rectangular roof plan of 59×77m, in which the up-curved 'load-carrying' cables and the down-curved 'pre-tensioning' cables were not lying in the same vertical planes as ordinary cable trusses, but staggered at a distance of half spacing, forming a spatial structural system with novel architectural shape. As a new type of cable roof structure the single-layer parallel cable system stiffened with transverse trusses or beams as called as 'cable-truss system' or 'cable-beam system' has been developed and applied in several sports buildings. In Anhui Gymnasium with a quasi-rectangular plan of overall dimensions 72×54m, parallel cables were suspended along the long direction of the plan, and steel trusses were erected transversely on the cables with a prescribed distance above the column tops. By depressing the truss ends to the columns by jacks a pre-stressed orthogonal cable-truss system with considerable rigidity was formed. It has been shown that this type of roof structure was behaving satisfactorily.

One of the trends in the construction of long-span roofs was to use some intermediate supporting structure, such as arches or rigid frames, in combination with cable nets or other suspended systems so that the middle part of the roof could be somewhat raised, an thus various combined roof system with novel architectural shapes were produced. In Sichuan Sports Hall with a hexagonal plan of overall dimensions 73.4×79.4m, a pair of slightly inclined reinforced concrete arches of span 102.5m were erected across the middle of the hall with a raise of 39m, and two trapezoidal cable nets were suspended between the arches and peripheral reinforced concrete beams. In Qingdao Sports Hall with a quasi-elliptical plan of 73×89m a similar pair of arches were adopted as the central supporting structure, and two semi-elliptical parts of the roof were covered by cable nets. The Chaoyang Gymnasium with a peach-pit-like plan of 66×78m built for the 1990 Asian Games was composed of two cable nets, and a special 'cable-arch system' was employed as the middle supporting structure. The central cable-arch system itself was a mixed structure, consisting of a pair of suspended cables and a pair of latticed steel arches, connected by vertical and horizontal linking members, forming a special bridge-like space structure. It has been revealed that such a cable-arch structure had much higher stiffness to resist unsymmetrical loading than simple suspended cables and was more economical than simple self-standing arches.

On the basis of engineering experience and the parallel theoretical/experimental studies, the "Technical Specifications for Cable-Suspended Structures" have been compiled and are now under inspection for approval. However, the development of cable structures has been somewhat slowing down since entering the 1990s. The main cause seems to be the lack of special construction teams for erecting cable structures that would be enough for the designers to hesitate to adopt such type of novel structure, though its construction technique is practically not so complicated. Recently the situation has been changing with the growing interest in tensile membrane structures, which could be considered as some evolved and modernized form of the traditional cable-tensioned structures. Some special corporations for membrane constructions have been established. The new Shanghai Stadium completed in 1997 adopted membrane roof supported on steel frames to cover the stands with a total area of 36100m^2. It was the first time in China to use membrane structure of large scale. There have also been erected several membrane constructions with smaller dimensions. The membrane material of required quality has to be imported yet, and the membrane constructions are still relatively expensive. However, a trend can be noticed that designs with membrane have often been proposed for important constructions and are usually warmly responded to. Many researchers have been involved in the theoretical study on problems encountered in design and construction of membrane structures. It is expected that such type of innovative structure would soon become an active member in the family of spatial structures.

4. Theoretical Research

Theoretical research on spatial structures has been carried out parallel to the engineering application of these structures. In the first stage the main efforts were concentrated to the study of basic behaviors under loading and the method of analysis of different types of spatial structures in order to meet the basic requirements of designing these innovative structures. During the 1970s and the early 1980s more attention of researchers was attracted to the development of analytical methods based upon "continuum theory", which treats the discrete structure assembled of individual members as a continuous system, such as the plate-analogy method for space truss, the shell-analogy method for reticulated shell and various analytical methods for single- or double-layer cable system and cable nets with various peripheral conditions[5]. These analytical methods are usually approximate and applicable only to certain specified forms of structures. With the popularization of computers, the finite element analysis method and the corresponding CAD programs have been developing rapidly, and since 1980s most of the spatial structures have been designed with computer. In fact, it would be very difficult to design a large-scale reticulated shell assembled of thousands of members and joints without the help of CAD programs. However, it is worth to indicate that the simple analytical methods are still useful for some types of cable structures. For example, the analytical formulas for pre-stressed double-layer cable system can provide rather complete and satisfactory results, accurate enough for practical design. In fact, the cable roof structure of Jilin Skating Rink was analyzed by hand calculating.

As a distinguishing feature of the research work in China, a large amount of experimental work has been conducted. The static and dynamic behaviors of nearly every important spatial structure were investigated by model test or site measurement. The results obtained from these investigations, together with those of the theoretical studies, provide comprehensive understanding of structural behaviors of different types of spatial structures, and have formed a solid theoretical foundation for the development of these structures in China.

The study on stability problem of reticulated shells as one of the more basic theoretical areas has been attracting attention of many researchers, and valuable results have been obtained. The stability analysis is known as the key problem for the design of reticulated shells. The stability characteristics of a complicated structure such like reticulated shell can be revealed clearly and accurately by complete load-deflection response analysis, in which the structural response under loading is regarded as a continuous process rather than some individual structural properties such as critical load, buckling mode, etc. The complete load-deflection curves give a more perfect picture about the behaviors of the structure. With the development of non-linear finite element analysis and methods for tracing equilibrium path, it can be said that the problem of complete load-deflection response analysis of prototype reticulated shells has been well solved from the viewpoint of theoretical side. Special programs have been compiled and successfully used for stability evaluation of large-scale reticulated shells.

However, engineers working in design practice still feel puzzled when dealing with stability problems of reticulated shells. The theoretical method as discussed above seems to them too complicated for direct application. So it is desirable to propose some kind of design formulas, reflecting the recent advances of theoretical study but simple in form for the convenience of practical application. For this purpose a comprehensive parametric analysis of stability behaviors of different types of single-layer reticulated shells with varying geometric and structural parameters has been carried out based upon complete load-deflection analysis with consideration of the effects of initial geometric imperfections and unsymmetrical distribution of loads. The "Consistent Mode Method" is proposed for the imperfection analysis. This method assumes the geometric imperfection of a reticulated shell to be distributed in consistence with the buckling mode of first order of the structure, which is supposed to be very likely the most unfavorable for the expected limit load of the reticulated shell. More than 2800 examples of reticulated shells of prototype were analyzed, and the plentiful results obtained were thoroughly studied. As a result, practical formulas for predicting limit loads, obtained by regression analysis respectively for different types of reticulated shells, rather simple for application but based upon accurate theoretical procedure as described, have been proposed[6].

The dynamic response to seismic load of space trusses, as well as of reticulated shells is another area of study in which quite a few researchers have been engaged[7, 8]. The dynamic characteristics of these structures are quite different from those of the multi-story and high-rise buildings, the seismic response of which has been rather thoroughly studied. As it has been revealed, not only the first mode of vibration, but quite a few modes of different orders would contribute to the dynamic response of long-span spatial structures, and the effects of vertical earthquake load would be important for these structures. Comprehensive studies for determining dynamic coefficients for displacements and internal forces under seismic actions have been carried out for different types of space trusses and reticulated shells, based upon which suggestions about the earthquake-resistant design method of these structures have been proposed and adopted by the corresponding technical specifications. Similar research work has been done for cable suspended structures.

The initial equilibrium problem and the wind-induced response analysis have become the main interests of study for cable structures and membrane structures. The initial equilibrium analysis is a problem of significance for flexible tensile structures, by which an optimal combination of structural shape, pre-stressing pattern and peripheral condition of the structure should be determined. It is not easy to solve this problem satisfactorily, especially for the membrane structure. Some "shape-finding" programs for such kinds of structure based upon non-linear finite element analysis have been compiled. Nevertheless the initial equilibrium problem itself can not be considered as well solved, especially from the viewpoint of perfection of theory or the optimization of the method, and therefore it is still very interesting to many researchers.

The cable and membrane structures are well known as very sensitive to wind excitations, and the wind-induced dynamic response analysis is an important procedure in design of such kind of structures. Different from the dynamic characteristics of high-rise structures which are often studied, the natural frequencies of vibration of cable and membrane structures are distributed in a wide area with very small intervals, and many frequencies have nearly the same contribution to the dynamic response of the structure. As a result, the method of random vibration analysis usually used for high-rise structures - a kind of frequency domain analysis based upon mode-superposition - would not be effective for cable and membrane structures. Therefore some kinds of discrete methods based upon time domain analysis have been developed, which seem to be more convenient for the random response analysis of these structures subjected to wind excitations. Besides, the wind-induced dynamic response of membrane structures somewhat differs from that of the cable structures. The flexible membranes tend to show more evident aeroelastic interaction with the wind, while the cable structures with traditional rigid roofing are more likely to behave with a characteristics of steady and amplitude-limited random vibration. Therefore in some study the aeroelastic interaction of membrane with wind has been taken into consideration. For the purpose of practical application, a comprehensive numerical parametrical analysis based upon the theoretical procedure as discussed above has been carried out for hyperbolic paraboloid (HP) cable net structures with elliptical and rhombic plans and with different geometric, structural and load parameters [9]. The idea of dynamic coefficients, which are defined to modify displacement and inner force responses for geometrically non-linear systems, was proposed, and the values of dynamic coefficients were calculated for the cable net structures in the parametrical analysis. The results obtained were thoroughly studied, based upon which the suggestions for practical wind-resistant design of cable net structures have been recommended. Similar work has been carried out for membrane structures of HP type with rhombic plan and of umbrella type with square plan[IO].

It is believed that the progress of theoretical research as discussed would promote the further development of spatial structures in China.

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