Experimental Study on Full-sized Models of Arched Corrugated Metal Roof

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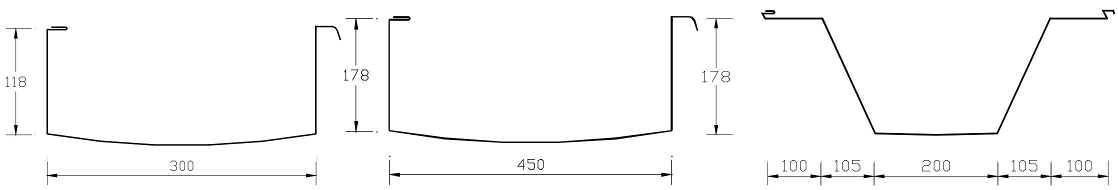
ABSTRACT

Nine groups of full-sized model experiments of arched corrugated metal roof were carried out herein. Through the description of the experimental processes and the analysis of the experimental results, the load bearing performance and the failure model of this kind of structure could be understood clearly. Based on the analysis of theoretical and experimental results, some valuable conclusions were summarized and recommendations for further studies were proposed.

1 INTROUDUCTION

Just like cold-formed light-gage steel plate, arched corrugated metal roof is made of color-coated galvanized steel sheet (usually 0.6～1.5mm thick) and coldly formed by special shaping machine. But because of the larger rigidity of the sections of its members and a load bearing style of arch structure, it can be used in larger span structures (more than 30m) not only as exterior protecting members but also as load bearing skeletons. With the plate-skeleton-combined structure style and the highly mechanized construction process, this kind of structure possesses so many advantages as strong spanning ability, light dead weight, high construction speed and beautiful configuration, and it is very suitable to be used in single layer buildings such as workshop, warehouse, auditorium, dining room, barracks etc. This kind of structure firstly appeared in America, and was introduced into China in 1992. Because of its good qualities, it has occupied the building market and been universally accepted in China by now.

According to the different shapes of the member sections in this kind of structure, it can be divided into three types that are respectively named MMR-118, MMR-178 and MMR-238 in China (Fig.1). From fig.1 we can see that, it is a typical kind of thin-walled steel structure. The research work on ordinary cold-formed thin-walled steel structures has been done thoroughly and the achievements can be found in Specifications for the design of them issued by many countries. Nevertheless, for some reasons, the research work on arched corrugated metal roof lags seriously behind its engineering practice. None of the rules for the design, construction and acceptance of this kind of structure have been published all over the world so far. In the winter of 1996, a heavy snow fall in the north-east of China caused more than 30000 m^2 of this kind of roof to collapse. In fact, all these structures had been calculated and designed with a special software designed by a Korean company. According to the design documents, these structures have quite high safety coefficients and shouldn’t collapse under this snow load. From this we can see that in order to keep the healthy development and promote the further dissemination of this kind of structure, it brooks no delay to carry out theoretical and experimental research on it systematically and thoroughly.



(a) MMR-118 (b) MMR-178 (c) MMR-238

Fig.1

According to the former research work, There are mainly two kinds of mechanic models for this kind of structure, namely arch and shell. So there are two kinds of numerical methods for the analysis of it, i.e, FEM of plan frame and FEM of shell. However, for such construction characteristics as thin wall, doubly-curved space configuration and corrugated siding, none purely theoretical analysis on this kind of structure can make satisfactory results[1], so experimental studies are essential here. Only combined with model tests and verified by experimental results can theoretical analysis make satisfactory results. However, just because of the construction characteristics, it is impossible to carry out scale model test of it, so full-sized model tests are indispensable to the research of this kind of structure.

After the engineering accidents mentioned above, the authors of this paper had carried out nine groups of full-sized model experiments of this kind of structure on the spots of these accidents . Through these model tests the cause of these accidents and the load bearing performance of this kind of structure could be understood. By comparing the theoretical results and the testing results, the great divergences between them could be seen clearly. Aiming at reducing these divergences, some recommendations for further studies are proposed in the last of this paper.

2 OUTLINE OF EXPERIMENT

2.1 Model specimens

All these tests were on-the-spot tests. The models studied here were the very structures that survived from that heavy snow fall. The steel plate used in these models had the yield strength of 280Mpa and Young's modulus of 2.06×10^5 MPa. Two kinds of span were chosen, i.e, 33m and 22m, and the section type of the trough plates of these models were the same as that shown in fig.1c. In all these models, eight were composed of four pieces of trough plate and only one was composed of six pieces of trough plate. So there were two kinds of width of the cross section of all these models', i.e, 2440mm and 3660mm. The cross section of the former is shown in fig.2. In order to search for an effective measure to raise the load bearing capacity of this kind of structure three models were reinforced by tension chords. The reinforcing pattern are shown in fig.3. The geometrical size and load patterns of all these models were described in tab.1. The models of 33m span were supported on a ring beam fastened on the top of the columns, while the models of 22m span were supported on special pedestals. Because the width of these models was very small compared with their span, their lateral rigidity was quite low. To avoid the lateral buckling model and something unwanted, scaffolds were placed under and by both sides of these models. The scaffolds that were placed upper these models were for the convenience of the application of load. The outlook of a model after being put in order is shown in fig.4

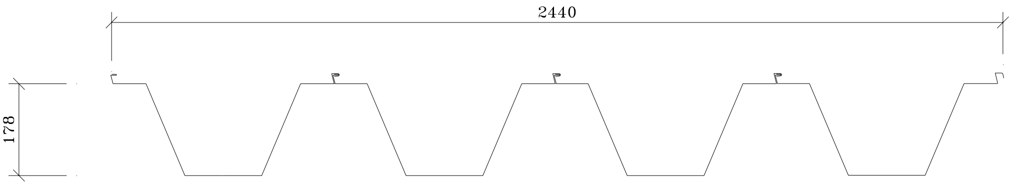
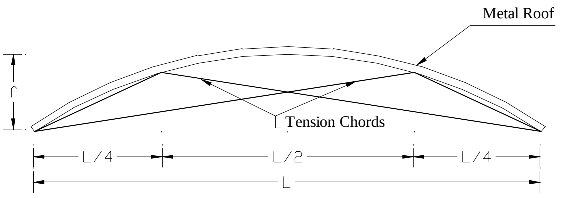


Fig.2 The Cross Section of Models



(a) The reinforcing pattern

Fig.3

Fig.4 Testing Ground

Tab.1

No.	**Arch span**	**Arch rise**	**Plate thick.**	**Lateral width**	**Load pattern**	**Remarks**
1	33(m)	6.6(m)	1.25(mm)	2440(mm)	Full span	
2	33(m)	6.6(m)	1.25(mm)	2440(mm)	Half span	
3	33(m)	6.6(m)	1.25(mm)	3660(mm)	Half span	Local distributed load
4	33(m)	6.6(m)	1.25(mm)	2440(mm)	Full span	Reinforced
5	33(m)	6.6(m)	1.25(mm)	2440(mm)	Half span	Reinforced
6	22(m)	4.4(m)	1.00(mm)	2440(mm)	Full span	
7	22(m)	4.4(m)	1.00(mm)	2440(mm)	Half span	
8	22(m)	4.4(m)	1.00(mm)	2440(mm)	Half span	Triangular load distribution
9	22(m)	4.4(m)	1.00(mm)	2440(mm)	Half span	Reinforced

2.2 Loading method

As a kind of thin-walled structure, arched corrugated metal roof is very sensitive to concentrated load. This load pattern may cause local buckling of the structure at a relatively low load lever. In actual engineering, large concentrated load should be avoided. To simulate the actual situation of load bearing of this kind of structure, distributed loads were applied by using sandbags. To avoid sliding of these sandbags on the surface of trough plates, special measures were taken. From tab.1 we can see that No.3 model bore local half-span distributed load. This means that only four out of the six trough plates bore half span distributed load, while the two edge trough plates were free from any external direct loads. By this loading method, we can see the effects of this model's lateral width on its load bearing capacity, and the coordination situation of these six trough plates. Tab.1 tells us that No.8 model bore triangularly distributed load. This loading pattern is to imitate ununiformly distributed snow load.

2.3 Observation method

Examinations of strains and displacements were indispensable for these model tests. Instrumentation used in these tests consists mainly of 7V08 static electrical resistance strainometer, theodolites and levelling instruments. Because this is a kind of flexible structure, its deformations are so large that any displacement measuring instruments with conventional precision can not cover its deformation scope, therefore levelling instruments were used to survey the vertical displacements, and theodolites were used to measure the rotary angles of those surveying points. Through the values of these rotary angles, we can figure out the horizontal displacements of those points.

The surveying points of displacements and strains were arranged at such locations as two springs, L/8 section, L/4 section , L/2 section, 3L/4 section and 7L/8 section.

3 EXPERIMENTAL RESULTS

The ultimate load, maximum horizontal displacement(U) and its location, maximum vertical displacement(V) and its location of each model were listed in tab.2

Tab.2

No.	Ultimate load	U	Location	V	Location
1	$0.87kN/m^2$	38cm	L/8	43cm	L/2
2	$0.56kN/m^2$	52cm	3L/4	57cm	3L/4
3	$0.27kN/m^2$	53cm	L/4	54cm	L/4
4	$0.92kN/m^2$	36cm	L/8	42cm	L/2
5	$1.02kN/m^2$	19cm	L/4	23cm	L/4
6	$1.06kN/m^2$	18cm	L/8	27cm	L/2
7	$0.54kN/m^2$	32cm	3L/4	41cm	3L/4
8	$1.02kN/m^2$	31cm	3L/4	39cm	3L/4
9	$1.28kN/m^2$	11cm	L/4	16cm	L/4

To make flat steel plate into arched trough plate, the webs and flanges of trough plate were rolled out many tiny ripples. On one hand, these ripples reinforced the stiffness of the plate, on the other hand they also made the distribution of stresses in the models complicated. Furthermore, all these tests were made in field, the changes of temperature and the blowing of wind made the stresses measured even more discrete. So although the cross sections of the models and patterns of external load were symmetric, the stresses in one section didn't show symmetry and it's almost impossible to find the laws of the distribution of stresses in the model sections. The direction of principal stress of a certain point always changed form time to time with the load added. Certainly the stresses measured couldn't reflect the laws of the distribution of the actual stresses, but as few of them exceed the yield point stress of the material, so they could qualitatively tell us it isn't strength that determined the load bearing capacity of this kind of structure. Although the width-to-thickness ratios of the trough plates in these models are very large, local buckling models, which is common for thin-walled members, didn't appear during these tests. This demonstrates clearly that the tiny ripples can strengthen the local stability of this kind of structure.

Both No.1 and No.6 models bore full-span uniformly distributed load, so their performances were similar. When the load level wasn't high, their deformations were symmetric, as shown in fig.5. But when the load was close to the ultimate load (shown in tab.2), a sudden change from symmetric deformation to dissymmetric deformation happened, and the central axis of the model moved to one side, which caused the internal forces around L/8 in this side to increase steeply. With a little more load and when the total load reached the lever shown in tab.2, the model lost its stability and buckled.

The buckling model of this kind of structure under half span distributed load was shown in fig. 6. It 's easy to find out that the stability bearing capacity of this kind of structure under half span load is much lower than that under full span load. Compared with full span load model, even though the external load value of half span load model was smaller , its stresses and displacements were much bigger. The reason was that the deviation between arch axis and pressure line in the model under half span load was much larger than that in the same model under full span load. So bending moments were prominent here, which was very disadvantageous to any structure. According to the data provided by the local meteorological department, after that snow-fall the basic snow load of the zone where the accidents happened was about 0.521kN/m^2, and the gale also blow snow from windward side to leeward side during the snow-fall. So the lever of the uneven half span snow load was close to the ultimate half span load listed in tab.2. we can say that half span load pattern is the most dangerous load pattern for this kind of structure.

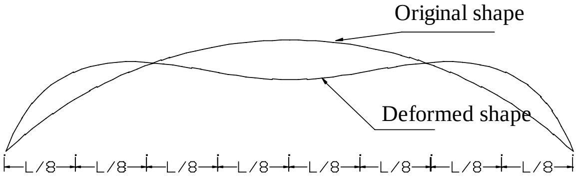


Fig.5 Deformation Shape of Full Span Load Model

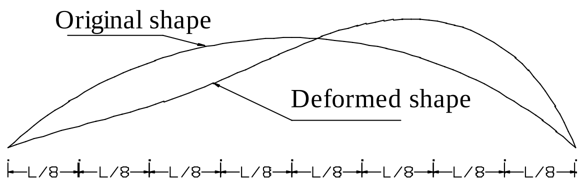


Fig6 Deformation Shape of Half Span Load Model

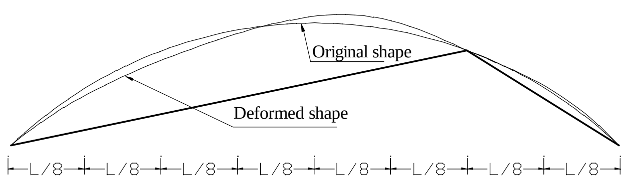


Fig.7 Deformation Shape of Reinforced Half Span Load Model

Though there were two pieces of trough plate free from direct external load, the ultimate load lever of No.3 model is not higher than that of No.2 model. This model test indicates that as a kind of thin-walled member with open cross section, its torsional rigidity was very small and its capacity of resisting torsional load was low. From this test we also can see the coordination between two pieces of plates was bad, and the lateral width of other models had little effect on their load bearing capacity.

Fig.7 shows that the deformation shape of the models reinforced with tension chords subjected to half span load. Tab.2 tells that the reinforcing pattern shown in fig.3 has little effect on the structure under full span load, while under half span load the load bearing capacity of the same structure can be doubled. From fig.7 we can see that two chords restrain the 3L/4 section, where the largest deformation will take place without these chords. The tension chords can make the distribution of the internal forces even more uniform.

4 COMPARISON OF EXPERIMENTAL AND THEORETICAL RESULTS

Because of the symmetry of the configuration and the load distribution along the longitudinal direction of this kind of structure, it can be looked as a kind of arch structure and simulated as thin-walled beam elements with finite element method. The material constants of this mechanic model, such as bending rigidity, torsional rigidity, etc, are calculated according the geometric size of unit width of the cross section of the structure.

Another FEA model analyzed here is shell. To reflect such structure characteristics as thin wall, tiny ripples, doubly-curved space configuration, shell element is the ideal one because it can imitate any space configuration distinctly. The shell element used here is a kind of generalized conforming quadrilateral flat shell element which was expressed in detail in ref.2. A piece of trough plate is chosen as calculating model. To simulate the working condition of one piece of trough plate in a roof structure, horizontal restraints are exerted on the edges of the flanges of the trough plate. Because the length-to-width ratio of the trough plate is very large, the size of shell element should be very small in order to avoid deformed grid dividing. So the number of the shell elements in a piece of trough plate is great. This of course may increase the amount of calculation, while on the other hand this also can raise the calculating precision.

In general, the steel material used in this kind of structure is isotropic. But because of the section geometric shapes of the ripples on the webs and flanges of the trough plate, the webs and flanges will respond to load orthotropically. To analyze the effect of the ripples, an equivalent orthotropic flat sheet is defined for the shell FEA model. The material constants of the equivalent flat sheet can be obtained according to the equivalent conditions[3].

The above experiments had indicated that it is global stability, not material strength, that control the load bearing capacity of this kind of structure, so only geometric nonlinearity is considered in this paper. For the same reason, local buckling isn't considered. To avoid the problem of material nonlinearity in theoretical analysis, yield criterion is adopted as the failure criterion. That is to say, if the calculated stress at any point in the structure reaches the yield stress of the steel (280 MPa), the structure is considered to fail. The corresponding load will represent the ultimate load of the structure.

By the programs developed for finite element analysis of the models above, this paper has calculated model 1, model 2, model 6 and model 7 described in tab.1. the ultimate loads of theoretical analysis and experiments and the errors of theoretical results compared with experimental results are listed in tab.3.

Tab.3

Model No.	Experiment	Arch model	Error	Shell model	Error
1	0.87kN/m^2	3.91kN/m^2	349.4%	1.65kN/m^2	89.65%
2	0.56kN/m^2	1.34kN/m^2	139.8%	0.93kN/m^2	66.07%
6	1.02kN/m^2	7.71kN/m^2	655.9%	3.86kN/m^2	278.4%
7	0.54kN/m^2	4.29kN/m^2	694.4%	1.82kN/m^2	237.0%

As a kind of thin-walled steel structure, it is very sensitive to any defects. Because the models used in these experiments were the survivors of the accidents mentioned above, which had been subject to heavy snow load, their actual original configuration are not the same as that in theory. Initial deformation and initial stress are inevitable here, which are very disadvantageous to the load bearing capacity of this kind of structure. In addition, all the tests were carried out out of door, wind load will bring harmful effects on the models too. So from tab.3 we can see all the theoretical results are much higher than the corresponding experimental results. Compared with half-span loading models, the errors of full-span loading models are even larger, which indicates that it's more sensitive to defects for this kind of structure under full span load.

The results calculated with shell FEA model is much closer to the experimental results than that calculated with arch FEA model. This indicates that even though it's symmetric along longitudinal direction, the arched trough plate, the structure's component, has the property of space load carrying because of its characteristics of thin wall and local ripple shape. The construction of ripples on the plate certainly can strengthen the stiffness along longitudinal direction, which makes the structure free from wavelike local buckling, but it weakens the stiffness along span direction. This is very disadvantageous for this kind of bearing structure. Shell FEA model can reflect these factors to a certain extend.

Through analysis above, it's not difficult to find out that any purely theoretical analysis on this kind of structure has a long distance from real application. Experiment is indispensable here. But experimental study requires testing of full-sized models which are very expensive and the result is only applicable for some special situations. So studying the relation between theoretical analysis methods and the experimental results and finding out the appropriate calculating constants from these experiments so as to revise the calculation programs have great significance for the research of this kind of structure. The authors of this paper are now preparing several groups of member tests in order to observe the material constants of this kind of arched rippled trough plate. These material constants got from experiments will be used in FEA.

5 CONCLUSION

Through the description of nine groups of full-sized model tests of Arched Corrugated Metal Roof, the load bearing performance and the failure model of this kind of structure are clear now. After pointing out that local buckling and material strength are not the control factors of its load carrying capacity, two kinds of FEA models were established for the theoretical analysis of it. Though the theoretical results didn’t agree well with the test results, these deviations indicate that such structural characteristics of this kind of structure as thin wall and local ripple shape have great effect on its load bearing performance. To reduce the difference between theory analysis and experiment study, recommendations for further research are proposed.

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