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DESIGN OF CABLE NET-MEMBRANE ROOFS WITH REVERSE CURVATURE BY NONLINEAR ANALYSIS

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Abstract-This study is to analyze for the design considerations and mechanical characteristics of the cable net-membrane roof. Because cable net-membrane systems have no compression members, the weight of the roof can be greatly reduced. The cables have very high tensile strength, but the flexural stiffness is very low, resulting in large deformations. In order to minimize the deformation of the flexible cable roof system the required rigidity should be ensured by introducing the prestress of cables. Cable net roof systems with upward and downward reverse curvatures can be reduced very effectively the deformation of the roof for the external loads. The reverse curvature cable system is an effective roof system for vertical loads. The cable element is defined as only transmitting tension, and the membrane element is assumed as occurring a membrane deformation, ignoring the coupling and out-of-plane shear deformation, so there is no stiffness in the direction perpendicular to the surface of the element. The triangular membrane element has only three degrees of freedom at the node. In this study, geometric nonlinear analysis of cable net-membrane with a reverse curvature roof system according to the sag ratio of ridge cables and the rise ratio of valley cables is performed to understand the mechanical characteristics of overall roof.
Keywords-Cable net-membrane roof, Reverse curvature, Cable element, Triangular membrane element, Geometric nonlinear analysis, Mechanical characteristics

1. INTRODUCTION

The cables are very high in tensile strength, but they have very low flexural stiffness occurring in large deformation. Therefore, the structural system with a small deformation as much as possible should be considered at building design, and the analysis considering geometric nonlinearity should be performed. In order to minimize the deformation of the cable roof system, it is should be ensured the necessary rigidity, a roof system with upward and downward curvatures is very effectively structural system. The cable roof system has that the ridge and valley cables are connected by bracing cables to resist the up and down load. The structural concept of a radial cable roof system is consists of outer compression ring and continuous radial truss cables. The outer circular ring acting compression forces is setting in equilibrium with the tensile forces of inner radial cables. The upper ridge cables and the lower valley cables with a large prestress are connected to ensure structural stability and rigidity. The ridge cables and the valley cables are prestressed in the reverse direction [1-4]. This paper is carried out analyzing and comparing the tensile forces of cables and deflection of curved roof systems by vertical loads. The elements for analysis uses a tension only cable element and a triangular membrane element with 3 degree of freedom in each node. The authors will estimate that the curved cable-membrane roof system with reverse curvature is one of a very effectively structural system according to the sag ratio of ridge cables and the rise ratio of valley cables.

2. STRUCTURAL CONCEPTS OF CABLE ROOF SYSTEMS

2.1 Types of steel cables-

Wire rope is consists of several strands of metal wire twisted into a helix as shown in Figure 1 . Steel wire ropes are normally made of non-alloy carbon steel with a carbon content of 0.4 to 0.95%. Cross lay strands have the wires of the different layers cross each other. In the mostly used parallel lay strands, the wires of any two superimposed layers are parallel. Spiral ropes are round strands as they have an assembly of layers of wires laid helically over a center. Spiral ropes can be dimensioned in such a way that the rope torque is nearly zero. The half-locked coil rope and the full-locked coil rope always have a center made of round wires. The locked coil ropes have one or more outer layers of profile wires. They have the advantage that their construction prevents the penetration of dirt and water to a greater extent and it also protects them from loss of lubricant. Stranded ropes are an assembly of several strands laid helically in one or more layers around a core. This core can be one of three types. The first is a fiber core, made up of synthetic material. Fiber cores are the most flexible and elastic. The second type, wire strand core, is made up of one additional strand of wire, and is typically used for suspension. The third type is independent wire rope core (IWRC), which is the most durable in all types of environments [5, 6].

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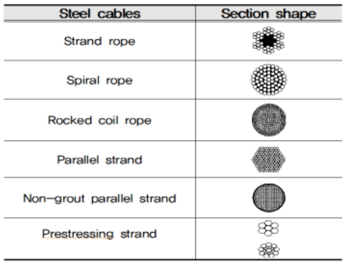


Figure 1. Section geometry of steel cables [5]

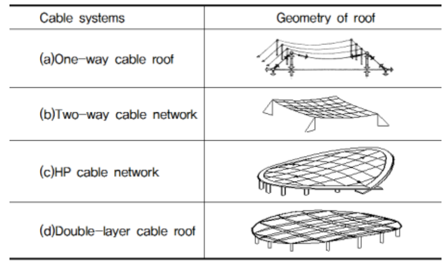


Figure 2. Systems of a cable network [5]

2.2 Design concepts of cable structures-

The mechanical characteristics of the cable as a structural member are that the force is transmitted only by the tensile forces, and the material characteristics of cables have high strength and light weight. The cable system is rich in shape finding and flexibility. There is no restriction on the member length and easy to carry. Cables having these advantages can be applied to the large span structures with lightweight roof alone or in combination with other structural elements. The use of cable systems in the large span roof and the structure with free form design can widen the possibility of the building construction in terms of economy and formability [5-12].

When using cables as structural members, it is difficult to expect the stability of cable system in a relaxed state. In order to ensure a stable tensile rigidity of the cable, a suitable tensile stress must be introduced into the cables, and in particular, in the case of a twisted rope, the effect of initial stiffness on structural behavior should be designed carefully. Even small errors in length or fixed location when installing cables can have a significant influence on the stress and strain of other structures connected to the cables. Therefore, a systematic review of the entire structure, details and methods of construction are required. It should be considered the curves of structures using the flexibility of the cable, and the effect of the constraint force and friction force of the fixed steel wire at the bending part. In order to consider the mechanical behavior of each cable, it is important to understand the role of cables for the stability of overall structures [5,6].

In order to introduce a pretension into the cables, it is necessary to check the information including the joint details and the construction method. The stability is required the tensile stress introduced to secure the linearity of the cable to the additional load, the tensile stress is generated in the equilibrium state in connection of the frame structures, tensile stresses intentionally is introduced into other structural elements to control stresses and strains, and the tensile stresses are introduced to stabilize the structural system by the cables [5,6].

2.3 Structural concepts of a cable network structures-

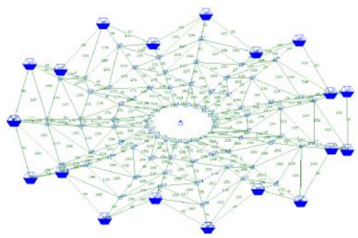
The curve of the cable net system is determined by the distribution of tension and the boundary condition of the cables as shown in Figure 2. The roof curves have in equilibrium state generated by the cables with the curvature of the opposite direction with Gaussian curves. Regarding each curved surface, the bi-directional curvature must be the inverse ratio by the tension force of cables, the entire curved surface is good to be a saddle type. The initial curved surface composed of only the cable is used as a starting curve when determining the surface by its self-weight or when calculating the deformation and stress due to external loads such as live load, wind load and snow load. How to determine the initial surface is as follows. (a)Use HP curved surface or its cutting shape with geometric curved surface. (b)Calculate the numerical equilibrium surface with specified tension surface. (c)Experiments for searching initial curve are obtained using a special model capable of introducing tension, and also can obtain the initial shape using the curve of soap surface [5,6].

The setting of the prestress introduced into the cables is an important design parameter to secure the rigidity of the suspension roof together with the determination of the initial curved surface. Moreover, the prestress depends on the increase of the stress level for structural stability. Therefore, it is difficult to balance the entire structures by affecting the boundary structure if it is given more than the required prestress. The presence of a prestress is particularly effective in controlling the deformations by an antisymmetric component of a local distribution load. One of the goals in the process of prestressing is to take the limit of loss of tension. That is, the forces caused by the change in tension should not lost, the pretress should be distributed almost uniformly on the roof surface. The prestress should be continued the tensile forces of the stabilizing cables against the snow load and the tensile force of the bearing cables against the load caused by the wind load, respectively. The amount of the prestress is expressed by the PS coefficient. This PS coefficient is the value obtained by the converted vertical load resulting from the tension forces and curvature of the downward pushing cable [5,6].

The suspension deflection to the span in the suspension direction and rise height of stabilizing cables are called sag ratio and rise ratio, respectively. In practice, it is often the case that the ratio takes about 0.05 to 0.10. The effect of deflection control by sag ratio is remarkable for loads distributed over a overall area. One of the characteristics of the suspension roof structure is that the tensile forces of the cables by the prestress and external force occurs a large horizontal reaction at the support. In the case of a suspension roof with a typical shape, the sum of the horizontal tensile forces at the boundary is often two or three times the overall load of the roof. The control of horizontal tensile forces includes the concept of important structural design that dominates the suspension roofs, including form design and economic evaluation. Intermediate support such as main cables, main arches, etc. can be inserted into the suspension roof with the intent of changing the interior space of the structure. In this case, the choice of whether to absorb the horizontal reaction forces into the intermediate structure by fixed support or suspension support will be the point on the structural design [5,6].

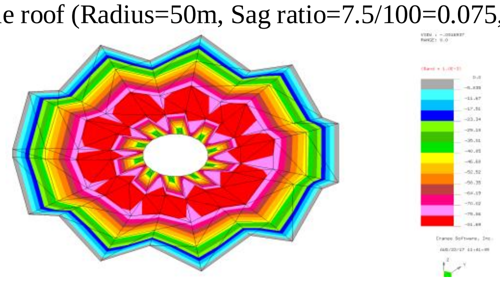
3. NONLINEAR ANALYSIS OF THE CABLE NETWORK-MEMBRANE ROOFS WITH REVERSE CURVERTURE

Many structures have a linear behavior, but there are accept where the relationship between force and displacement cannot be described properly with a model of linear behavior. The nonlinearity is due to the nonlinear behavior of the material, the geometric nonlinearity or combined effects. Cable structures always have a nonlinear behavior that has large displacement. The cable element for the geometric nonlinear analysis has been studied of great interest for many years. In 1638 Galileo says the form of trailing cable is parabolic, in 1691 Bernoulli, Leibnittz and Huygens brothers concluded that it has the curve shape of catenary. In 1891 Routh solved the equation for an elastic symmetrically suspended catenary comprised of linear elastic material. In 1981 Irvine adopts a Lagrangian approach to the solution of the elastic catenary obtaining an expression for the tangent stiffness matrix of non-symmetrical elastic methods [4]. The models of geometric nonlinear analysis are two cases of the circular and rectangular roof composed of cable net-membrane. The radius of a roof is 50m. The cable net is composed of the reverse curvature to resist effectively the vertical load. The sag ratio of ridge cable is 0.075, the rise span ratio of valley cable is 0.05.

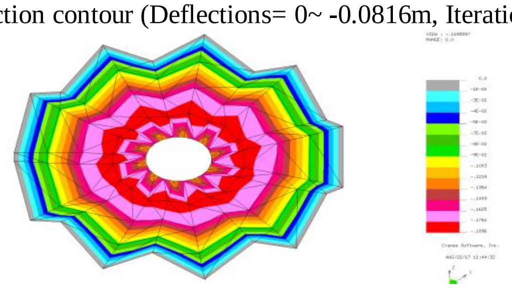


Item	Data
Elastic modulus	1.9×10^5 N/mm^2(Steel cable) 4.0×10^3 N/mm^2(Membrane)
Poission's ratio	0.49(Membrane) 0.3(Steel cable)
Cable diameter	60mm(Bearing cable) 60mm(Stabilizing cable) 30mm(Bracing cable) 90mm(Center ring cable)
Analysis data	Newton-Raphson algorithm Increment steps=300 Maximum iterations=30 Tolerance=1.000E-6
Pretension	Bearing cables=500kN Stabilizing cables=500kN Inner ring cables=700kN Bracing cables=30kN

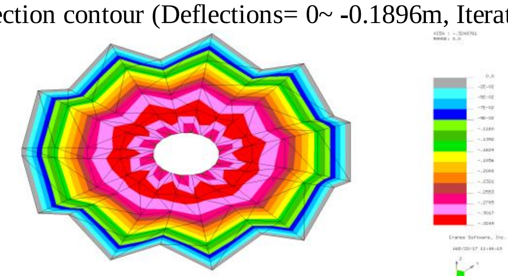
Figure 3. A circular cable net-membrane roof (Radius=50m, Sag ratio=7.5/100=0.075, Rise ratio=5/100=0.05)



(a) Deflection contour (Deflections= 0~ -0.0816m, Iterations=100)

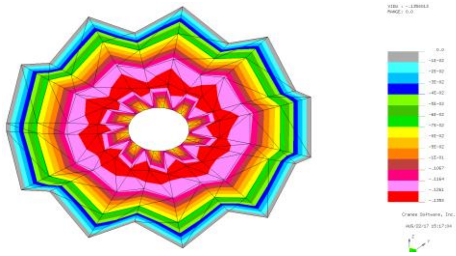


(b) Deflection contour (Deflections= 0~ -0.1896m, Iterations=200)

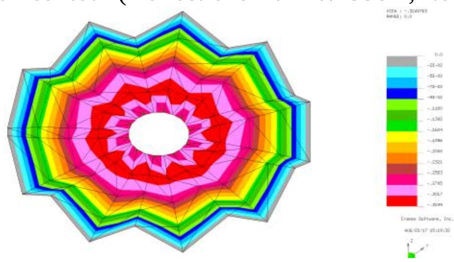


(c) Deflection contour (Deflections= 0 ~ -0.3249m, 3 Iterations=300)

Figure 4. Nonlinear analysis of a circular cable net-membrane roof (Pressure load=-1.0 kN/m^2)



(a) Deflection contour (Deflections= 0~ -0.1358m, Iterations=100)



(b) Deflection contour (Deflections=0~ -0.3249m, Iterations=200)

(c) Deflection contour (Deflections= 0~ -0.5189m, Iterations=300)

Figure 5. Nonlinear analysis of a circular cable net-membrane roof (Pressure load=-1.5 kN/m^2)

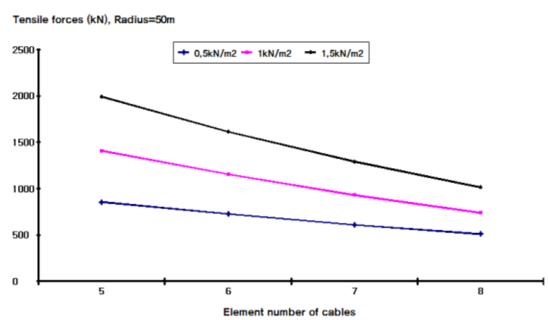
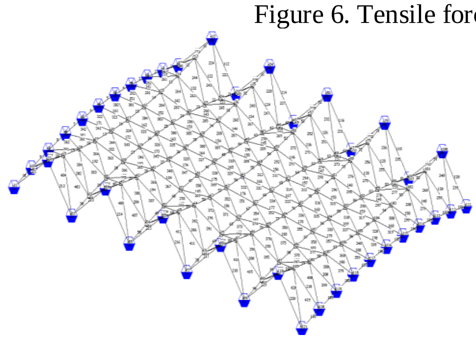
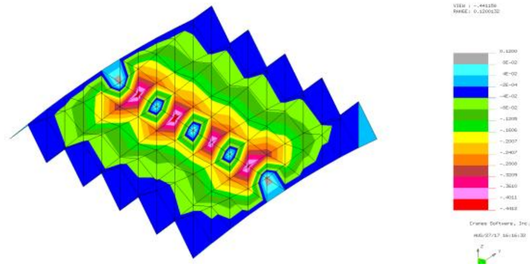


Figure 6. Tensile forces of ridge cables

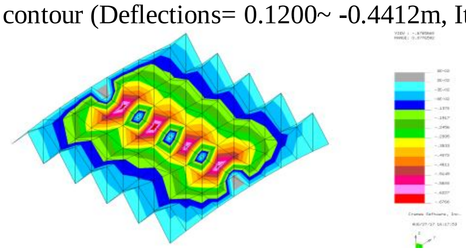


Item	Data
Elastic modulus	1.9x10^5 N/mm^2(Steel cable) 4.0x10^3 N/mm^2(Membrane)
Poission's ratio	0.49 (Membrane) 0.3(Steel cable)
Cable diameter	90mm(Bearing cable) 90mm(Stabilizing cable) 30mm(Bracing cable)
Analysis data	Newton-Raphson algorithm Increment steps=300 Maximum iterations=30 Tolerance=1.000E-6
Pretension	Bearing cables=200kN Stabilizing cables=200kN Bracing cables=50kN

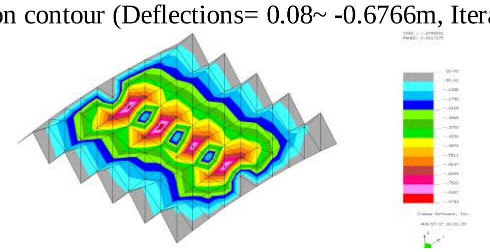
Figure 7. A rectangular cable net-membrane roof (Span=100m, Sag ratio=7.5/100=0.075, Rise ratio=5/100=0.05)



(a) Deflection contour (Deflections= 0.1200~ -0.4412m, Iterations=100)

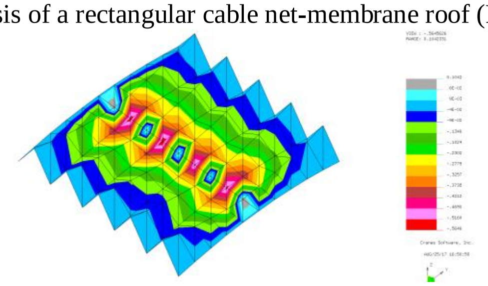


(b) Deflection contour (Deflections= 0.08~ -0.6766m, Iterations=200)

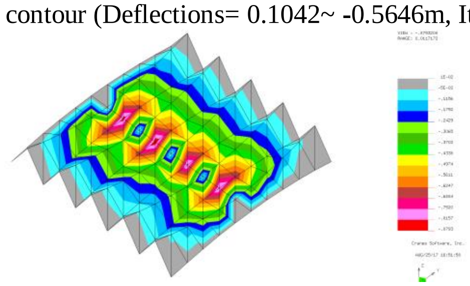


(c) Deflection contour (Deflections= 0.01~ -0.8793m, Iterations=300)

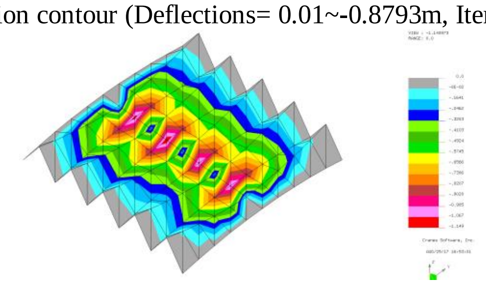
Figure 8. Nonlinear analysis of a rectangular cable net-membrane roof (Pressure load=-1.0 kN/m^2)



(a) Deflection contour (Deflections= 0.1042~ -0.5646m, Iterations=100)



(b) Deflection contour (Deflections= 0.01~-0.8793m, Iterations=200)



(c) Deflection contour (Deflections= 0~ -1.159m, Iterations=300)

Figure 9. Nonlinear analysis of a rectangular cable net-membrane roof (Pressure load=-1.5 kN/m^2)

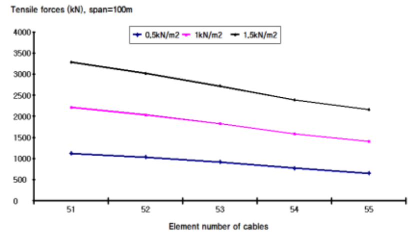


Figure 10. Tensile forces of ridge cables

4. CONCLUSION

This research was to analyze for the design considerations and structural characteristics of the cable net-membrane roof system that act vertical load in according to a reverse curvature.

(a) The cable net-membrane roof system is installed in the reverse direction of the ridge cables and the valley cables, and the inclination of the roof is controlled by the sag ratio of ridge cables and the rise ratio of valley cables. The overall structures can be obtained the required stiffness of structures by initial pretension of cables.

(b) The cable net roof is the system that can resist the up and down vertical loads very effectively by the reverse curvature of cables for snow load and wind load.

(c) In a result of the geometric nonlinear analysis on the whole roof, the deflection of roof and tensile forces of cables are increased almost proportionally to roof loads.

(d) The curved cable-membrane roof system with reverse curvature is a very lightweight roof with small deformations for external loads.

(e) The prestress introduced into the cables is an important design parameter to secure the stability of overall structures and the rigidity of the suspension roof with the determination of the initial curved surface.

(f)The circular cable roof system is more mechanically effective than the rectangular roof system. Not only the tensile strength of cables but also the deflection of a roof was occurred smaller.

5. ACKNOWLEDGEMENTS

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