水稻育苗中心輸送桁架之電腦輔助結構分析

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摘要

鋼桁架空中輸送機為國內水稻育苗中心常用的搬運系統；該類桁架單跨距長，負載重，因而傳統的桁架結構都非常厚重。臺灣大學生物產業機電工程學系與宜蘭技術學院生物機電工程系合作研發了一種以標準商品鋼管構成，具有構材取得容易，重量輕（成本低），附設系統維修與操作方便等優點的新型輸送桁架。國內對各類農用桁架做基本結構分析的文獻皆很少見；本研究即以電腦輔助有限元素法模擬分析新式桁架的基本結構特性，以為設計改進的參考。研究使用的電腦軟體為 ANSYS 5.5。分析中將桁架簡化成簡支樑模式，靜態分析其對應負荷之應力與變形，並求取其無外加負載，及假設其上佈滿苗盤與秧苗時的最大單跨距。動態分析則求取此最大跨距下的前十個自然振動模式與頻率。結構之破壞以最大剪應力破壞理論，安全因素 2 為檢驗準則；而且最大形變量不得超過 20 公分。分析結果顯示，桁架應力與變形最大處皆出現於桁架中央。無外加負載時，桁架的最大跨距為 30 m；滿佈苗箱與秧苗時則為 24 m。結構的重量為對其本身主要的負載，而跨距對桁架負載能力影響很大。而自然振動之前十共振頻率範圍自 1.72 至 15.79 Hz，且第三共振頻率（4.45 Hz）接近農業動土作業的振動頻率，故桁架應避免負載此類機械設備。

關鍵詞： 桁架、有限元素分析法、鋼結構分析

Computer-Aided Structural Analysis of a Steel Frame Used as Transportation Gantry in Rice Nursery Centers

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Abstract

Steel gantries were widely used as a transportation system in rice seedling nursery centers in Taiwan. These gantries were of long span and usually carry heavy loadings. The structure is structurally strong, but also bulky and heavy. A more compact gantry was developed in this paper. This new gantry used off-the-shelf standard steel pipes as structure members. It is much lighter and costs less than the conventional gantries. The structural characteristics of neither type of the gantries mentioned above have been thoroughly studied in Taiwan. The objective of this research was to study the structural characteristics of the newly developed gantry using computer-aided finite element analysis method. The static analysis included studied the element stresses and deformations of the structure under structural weight and under add on external loadings. One major goal was to identify the maximum length of single span of the gantry while the gantry carried no external load; and while the gantry was fully loaded with rice seedlings and their containing trays. The first ten natural frequencies and mode shapes of the maximum span gantry were than identified in modal analysis. The results showed that the maximum stress and deformation both occurred at the member located near the center of the gantry. The maximum length of single span of the gantry with no external load was 30 m; and was 24 m while the gantry was fully loaded with seedlings and trays. The length of gantry span seriously affected the load carrying capability of the gantry. The first ten natural frequencies ranged from 1.72 to 15.79 Hz. The third one, 4.45 Hz, is closed to the vibration frequency of agricultural tillage operations. The gantry should avoid carrying any tillage equipment.

Key Word: Gantry, Finite Element Method, Steel Structure Analysis

I. Introduction

Steel gantries were widely used as transportation system in rice seedling nursery centers in Taiwan [1]. Applications of gantries in other agricultural operations are also very common. As controlled traffic application, these gantries rode on fixed rails over seedling acclimatization fields within rice seedling centers to transport seedlings in and out of the fields. To fit with the size of the acclimatization fields, they were designed and made to be long span gantries (some could reach 33 m), and usually carry heavy loadings. To cope with the long span and heavy loadings, conventional designs of these gantries were structurally strong, but were also bulky and heavy. Possibility of over-design existed. The cost of these gantries was expensive due to the need for large quantity steel as construction material, and the usage of trapezoid cross-sectioned structure member that need be specially designed and manufactured. A more compact gantry system was developed jointly by the Department of Bio-Industrial Mechatronics Engineering, National Taiwan University; and the Department of Biomechatronic Engineering, National Ilan Institute of Technology [2]. This new gantry used off-the-shelf standard steel pipes as structure members, thus cost less than the conventional gantries. It is also much lighter (26 kg_f/m), and maintenance and operation of the equipments attached on the gantry were also easier. The structural characteristics of neither type of the gantries mentioned above have been thoroughly studied in Taiwan. The objective of this research was to study the structural characteristics of the newly developed gantry using computer-aided finite element analysis method. One major goal was to identify the maximum length of single span of the gantry while the gantry carried no external load; and while the gantry was fully loaded with rice seedlings and their containing trays under the restrictions of actual field operations and the limitation of structure strength.

II. Material and Method

1. The Subject Gantry

The subject gantry (Figure 1) was constructed of 4 types of commercial steel pipes (specifications listed in Table 1) that were made from S45C steel (material properties listed in Table 2). The cross-section of the gantry was inverse-triangular shape with the top-wider-side to accommodate belt conveyor and other add-on equipments. The height of the cross-section was 0.4 m, and the width of the topside was 0.6 m. The positions of the 4 members in the structure were shown in Figure 2. The gantry was constructed by several frames, each of 6 m long, using flanges and screw bolts to the required length. So the length of the gantry could only be the multiple of 6 m.

2. Modeling and Analysis

Finite element method was applied to perform analysis in this study. Computer software package ANSYS 5.5 was used as the analysis software [3]. Since 6 m section-frame was first manufactured and the gantry was constructed from certain number of section-frames, computer model of a section-frame was developed as the basic analysis model. First, AautoCAD was used to draw the geometry model of the structure (shown in Figure 3), and to locate the coordinates of nodal points of the structure. The nodal point coordinates were than used in the finite element model development, which was accomplished in ANSYS. Models longer than 6 m were built by connecting the models of section-frames. ANSYS element Beam 4 (3-D elastic beam, 6 degree of freedom) and Pipe 16 (elastic straight pipe, 6 degree of freedom) were selected to model the structure members with data needed for ANSYS inputs listed in Table 1. Because both ends of the gantry rode on fixed rails through end-supporting-frames in actual application, the gantry was modeled as simple supported beam with the end-supporting-frames temporarily omitted to simplify the calculation and to concentrate on the main structure of the gantry. One finite element model of a section-frame was shown in Figure 4.

In static analysis, the structural characteristics of gantries with span of 6 m, 12m, etc., up to impractical length in an increment of 6 m were studied. Stresses and deformations of the gantry members with no external loading; and fully loaded with seedlings and trays were examined from the simulation results. The seedling tray (the tray) was 0.60 x 0.30 m rectangle and contained three rolls of rice seedlings. Together, each tray and the seedlings it contained weighed 16 kg_f. In actual operation, the longer sides of the trays were aligned with the transportation direction on the conveyor belt. In the seedling and trays loaded cases, the number of trays that could set on the gantry was calculated. The total weight of the trays and seedlings set on the gantry was than calculated and assumed to be evenly distributed on the top members of the gantry (Figure 5). In no seedling and tray cases, the loading came solely from the weight of the gantry itself.

The main objective was to estimate the maximum length of single span of the gantry. Two restrictions limited the length of gantry span, the structural strength, and the allowable deformation of the gantry. To avoid touching of the gantry with the seedlings on the field, the maximum deformation of the gantry should not exceed 0.20 m. Maximum shear theory of failure and safety factor of 2 were applied to set the member stress limit in this study. Since all members were made from S45C steel with yield stress of 4.90 x 10^8 N/m^2, the maximum shear stress of any node or element exceeds 1.23 x 10^8 N/m^2 would be considered as structural failure.

Once the maximum single span of the gantry was determined, the first ten natural frequencies and mode shapes of the gantry with maximum span were then decided in the followed modal analysis processes. Animated-displaying functions in ANSYS post processing routine helped viewing the vibration motions more comprehensively.

III. Results and Discussion

1. Gantry with No External Loading

Simulated results of maximum deformations and shear stresses of various gantry spans while no additional loading was applied were listed in Table 3. In these cases, the structural weight was the solely load applied to the gantry. Example graphical displays of deformation and stress responses, though not in the original colorful contour plot form, were shown in Figure 6 and 7, respectively.

It is not surprising to see the high stresses and large deformations occurred at the members that were near the center of the gantry, as shown in Figure 6 and 7. Maximum stress and deformation both occurred at the bottom circular-pipe member located near the center of the gantry. While larger deformation existed at all the members around the center of the gantry, stress values of the two top square pipe members in the same area were not as high as those of vertical trusses and bottom circular pipes. Loading was transferred through the vertical trusses down to the bottom pipe, as expected. It seemed that in this design, the bottom circular pipe is the critical member.

Table 3 shows that the maximum span of the gantry is 30 m when no external loading was applied to the gantry. In this case, the total loading applied on the gantry (the weight of the gantry) was 780 kg_f (7644 N). The maximum shear stress was $1.19x10^8$ N/m^2, and the maximum deformation is 9.77x 10^{-2} m, the restriction of structural strength applied first.

2. Gantry fully loaded with rice seedlings and trays

Simulated results of maximum deformations and shear stresses of various gantry spans while the gantry was fully loaded with seedlings and trays were listed in Table 4. The structural respondent characteristics were similar to those of the no external loading cases as mentioned above. Maximum stress and deformation both occurred at the bottom circular-pipe members located near the center of the gantry. While larger deformation existed at all the members around the center of the gantry, stress values of the two top square pipe members in the same area were not as high as those of vertical trusses and bottom circular pipes. However, due to the additional loadings, the maximum allowable span was decreased down to 24 m, one section shorter. In this case, the maximum shear stress is 1.02×10^8 N/m^2, and the maximum deformation is 1.20×10^{-1} m, the restriction of structural strength applied first again. Considering in this case, the total weight of the rice seedlings and trays was 640 kg$_f$ (6272 N), the weight of the structure was 624 kg$_f$ (6115 N), the total loading applied on the gantry was 1267 kg$_f$ (12416 N), 1.5 times of the 30 m gantry with no external loading case. Structure weight appeared to be a major loading to the gantry itself; also the length of gantry span seriously affected the load carrying capability of the gantry.

3. Modal analysis

The first ten mode shapes of the gantry with span of 30 m were shown in Figure 8-(1) to (10). The natural frequencies were listed in Table 5. The mode shapes showed that motions of vibration included up-down and twisting movements of the gantry structure. The frequencies listed in Table 5 ranged from 1.72 to 15.79 Hz. Equipments or operations which will cause vibration frequency closed to these frequencies in actual operations should not be installed or carried out on the gantry. For example, the third frequency, 4.45 Hz, is closed to the vibration frequency of agricultural tillage operations. The gantry should avoid carrying any tillage equipment.

IV. Conclusion

A finite element computer model of the subject transportation gantry was developed to study the structural characteristics of the gantry. This model can be readily used for further studies. Simulation results showed that the maximum stress and deformation both occurred at the member located near the center of the gantry. The bottom circular pipe of the gantry was the critical member for it sustained the highest stress. The maximum length of single span of the gantry with no external load was 30 m; and was 24 m while the gantry was fully loaded with seedlings and trays. Structure of gantry would fail before the deformation went beyond allowable range if the limitation of span was exceeded. However, it should be noted that adding heavy operational equipments would surely further shorten the allowable length of the gantry span. The weight of the structure itself seemed to be a major loading to the structure in practical operations; also the length of gantry span seriously affected the load carrying capability of the gantry. Further research like optimum design aimed to find the best trade-off between the weight (the length of span), and the strength of the gantry structure, or to improve the original design would be valuable and should be encouraged.

The first ten vibration mode shapes and correspondent natural frequencies were identified. The natural frequencies ranged from 1.72 to 15.79 Hz. The third one, 4.45 Hz, is closed to the vibration frequency of agricultural tillage operations. The gantry should avoid carrying any tillage equipment. Any equipment or operation which will cause vibration frequency closed to these frequencies in actual operations should not be installed or carried out on the gantry.

It should also be mentioned that simplifications and assumptions were applied in building the simulation model. More detail simulation processes should be adopted to develop the model if very accurate analysis results were required.

V. Acknowledgement

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VI. References

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Table 1 Specifications of the structure members.

Member	Square pipe	Circular pipe 1	Circular pipe 2	Circular pipe 3
Description Dimension (mm)	Construction steel pipe 60×60	Construction steel pipe Do＝60.5	Construction steel pipe Do＝42.7	Construction steel pipe Do＝34.0
Thickness (mm)	2.3	3.2	2.8	2.3
Weight/m kg_f/m	4.06	4.52	2.76	1.8
Area of Cross-section (cm^2)	5.172	23.7	3.510	2.291
Moment of Inertial (cm^2)	28.3	23.7	7.02	2.89
Yield Stress (kg_f/mm^2)	50	50	50	50
Tensile Stress (kg_f/mm^2)	70	70	70	70

Table 2 Material properties of S45C steel.

Material	Young's modulus	Density	Poisson's ratio
S45C	200×10^9 N/m^2	7900 kg/m^3	0.3

Table 3 Maximum deformations and shear stresses of the gantry with various spans, no external loading.

Length of gantry span (m)	Maximum Deformation (m)	Maximum shear stress (N/mm^2)
6	0.223×10^{-3}	0.680×10^{7}

12	2.608×10^{-3}	0.227×10^{8}
18	12.54×10^{-3}	0.467×10^{8}
24	38.47×10^{-3}	0.788×10^{8}
30	97.71×10^{-3}	0.119×10^{9}
36	190.6×10^{-3}	0.167×10^{9}
42	351.4×10^{-3}	0.224×10^{9}
48	597.4×10^{-3}	0.288×10^{9}

Table 4 Maximum deformations and shear stresses of the gantry with various spans, gantry fully loaded with rice seedling and trays.

Length of gantry span (m)	Maximum deformation (m)	Maximum shear stress (N/mm^2)
6	0.289×10^{-3}	0.887×10^{7}
12	3.377×10^{-3}	0.294×10^{8}
18	16.231×10^{-3}	0.605×10^{8}
24	49.8×10^{-3}	0.102×10^{8}
30	119.996×10^{-3}	0.154×10^{9}
36	246.723×10^{-3}	0.217×10^{9}

Table 5 Natural frequencies of the first ten vibration modes.

Mode	Natural frequency (Hz)
1	1.7225
2	1.8671
3	4.4497
4	5.0646

5	6.7194
6	8.3163
7	9.7391
8	11.818
9	14.788
10	15.788

Figure 1 Photograph of the subject gantry in field operation.

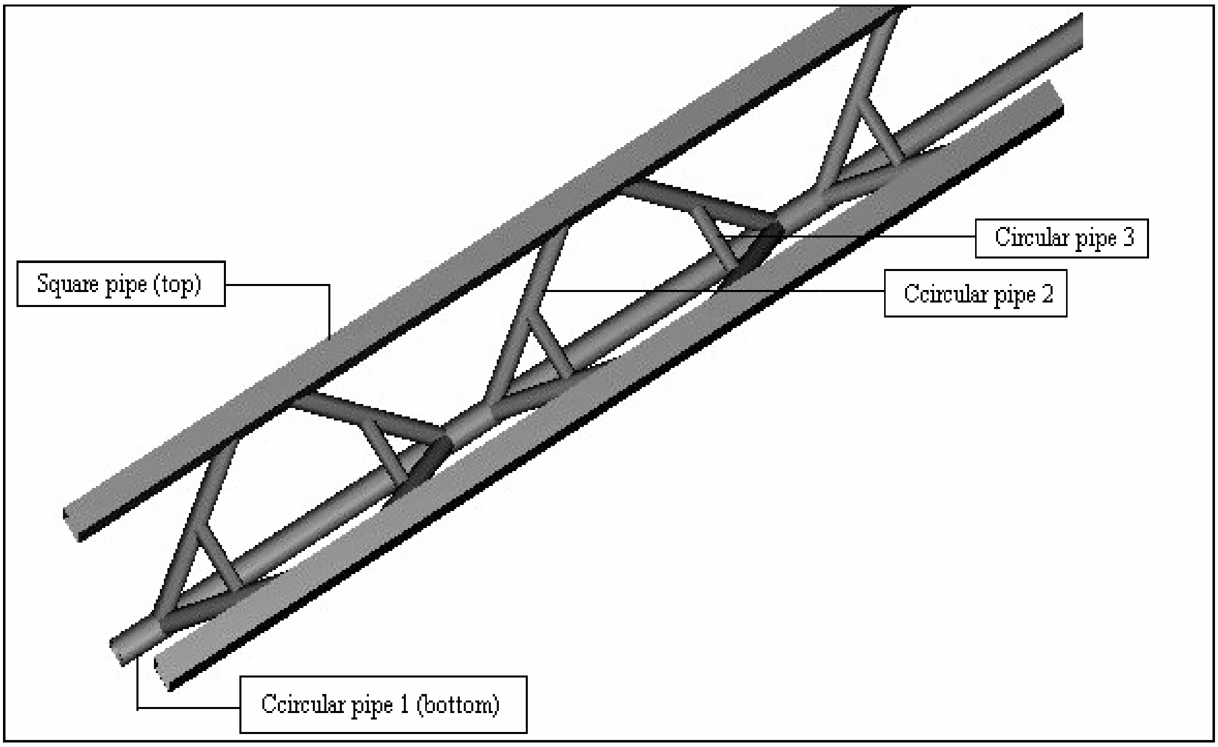


Figure 2 Four structural member types and their locations in the structure.

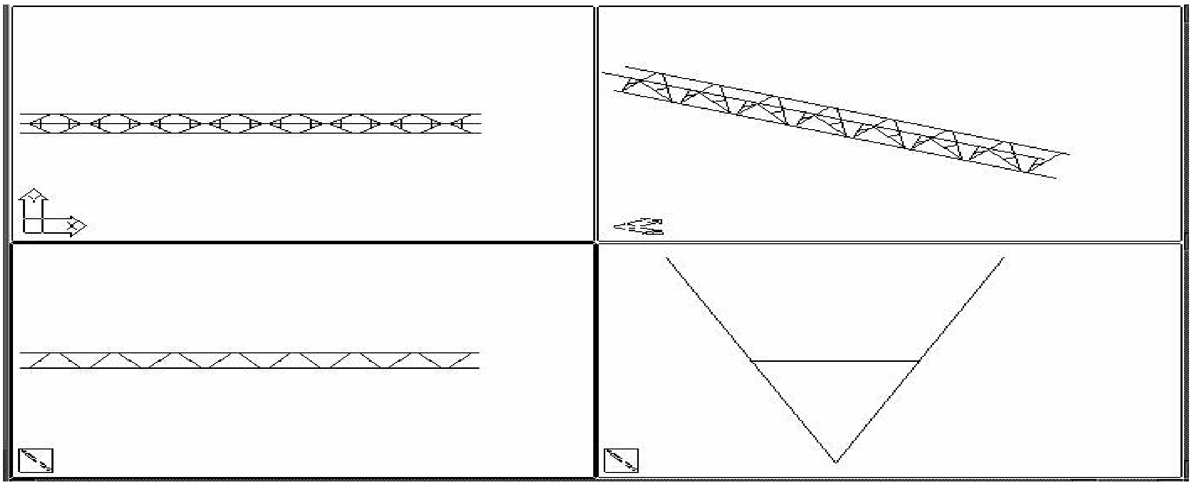


Figure 3 Geometry model of the 6 m section-frame developed using AutoCAD.

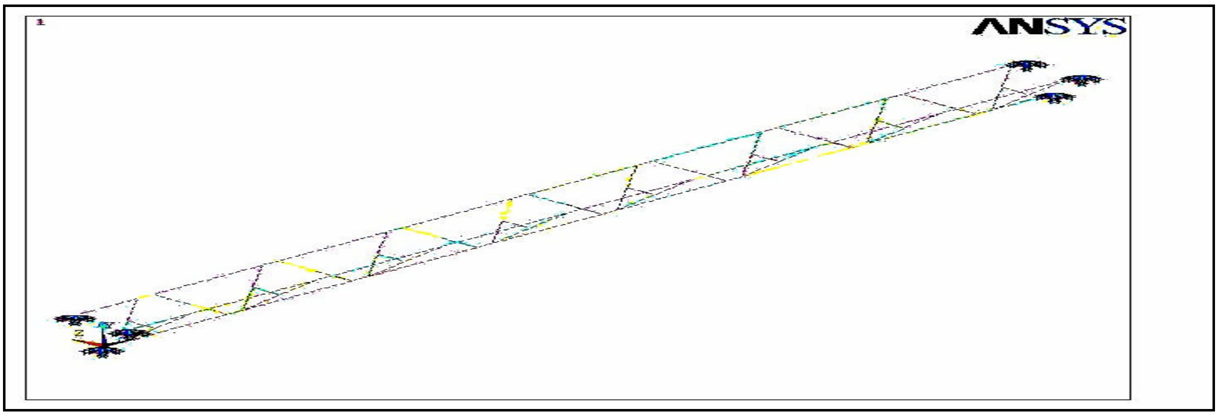


Figure 4 Finite element model of the 6 m section-frame developed in ANSYS.

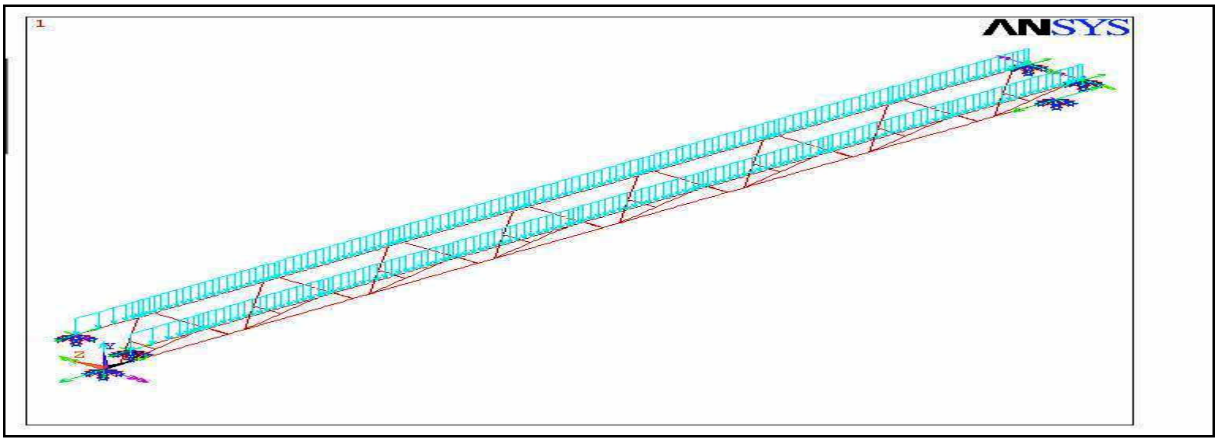


Figure 5 Simulated distributional loading of seedling and trays on the gantry.

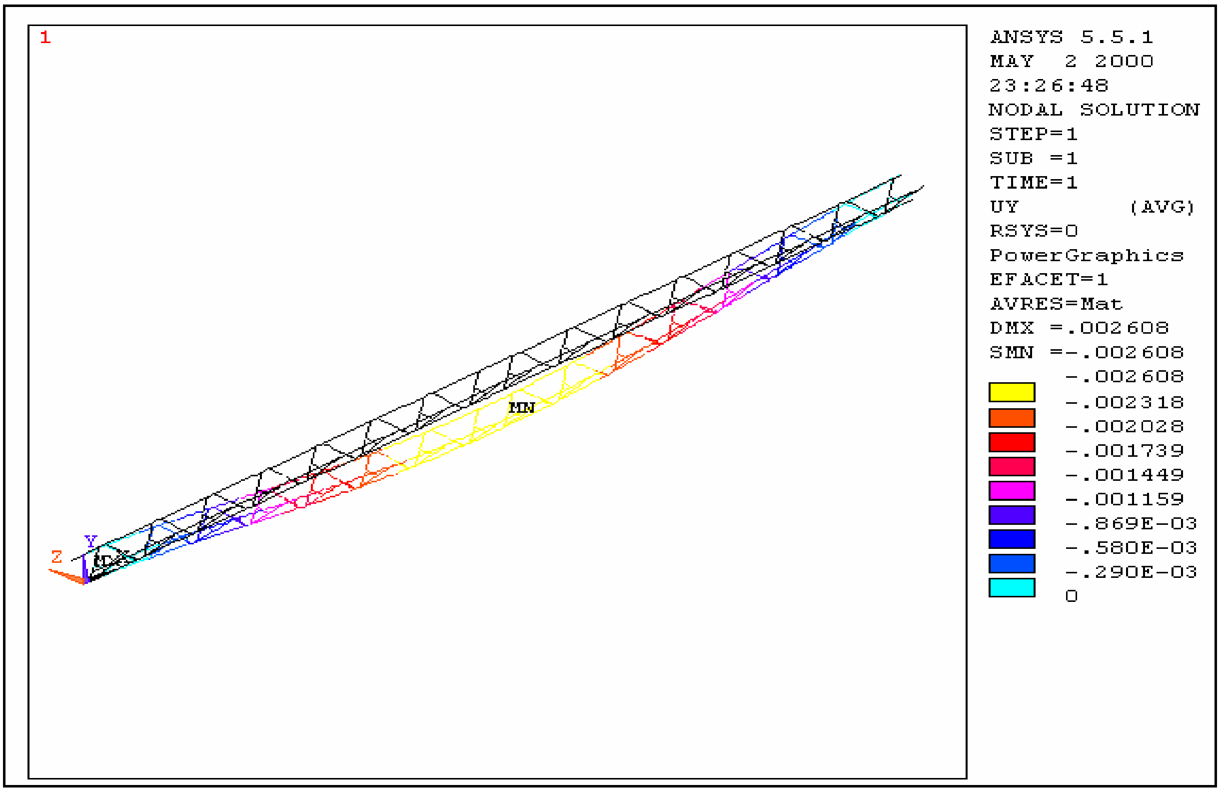


Figure 6 Example of deformation contour plot, no external loading, 12m gantry span.

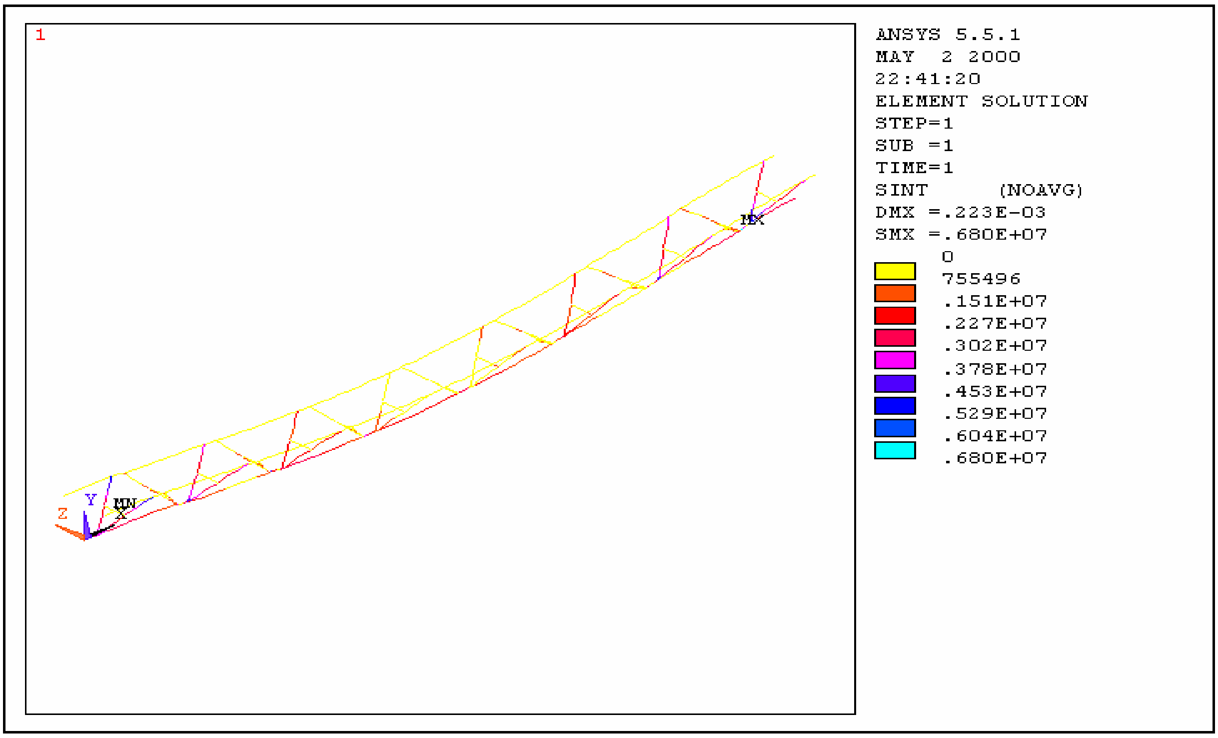
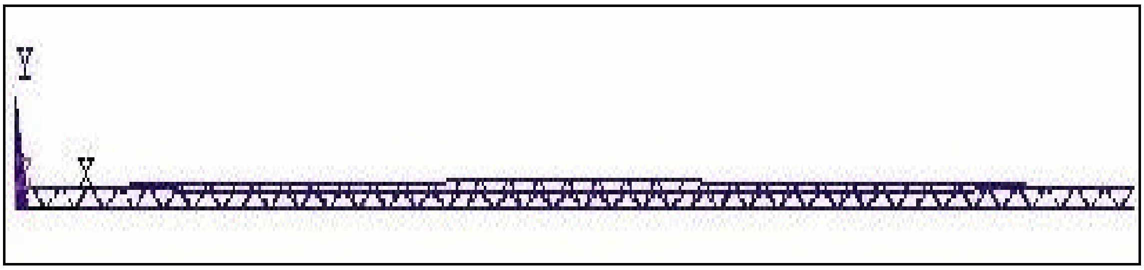
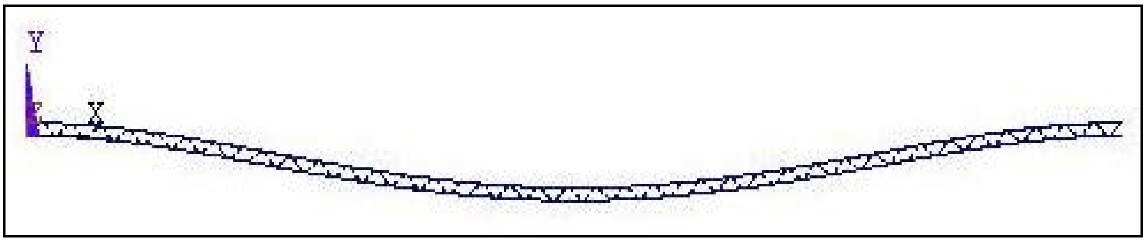


Figure 7 Example of stress contour plot, no external loading, 6 m gantry span.



(1)



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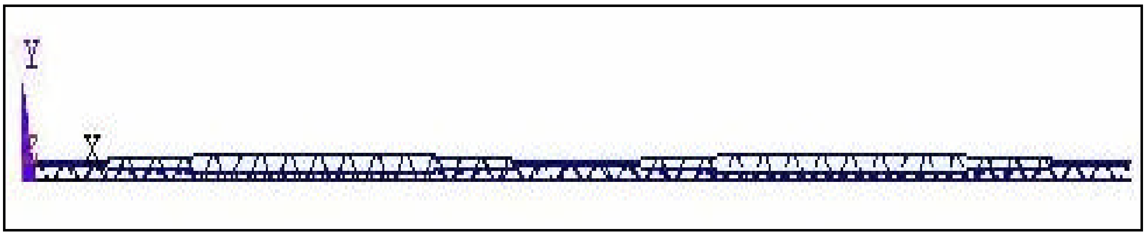

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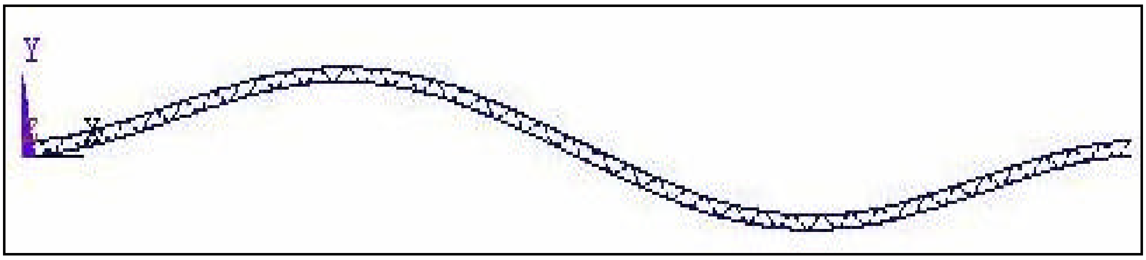

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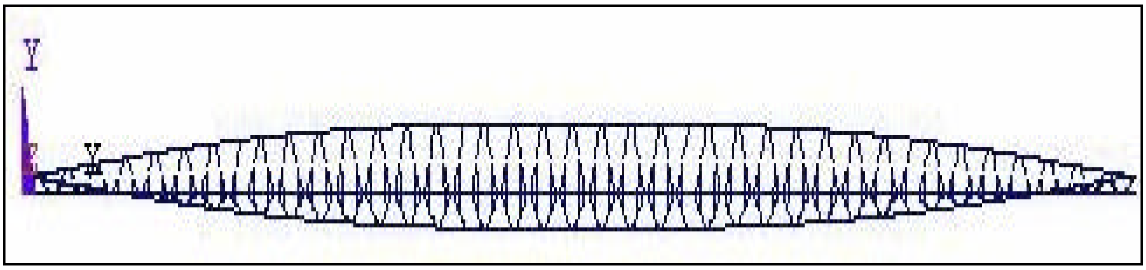
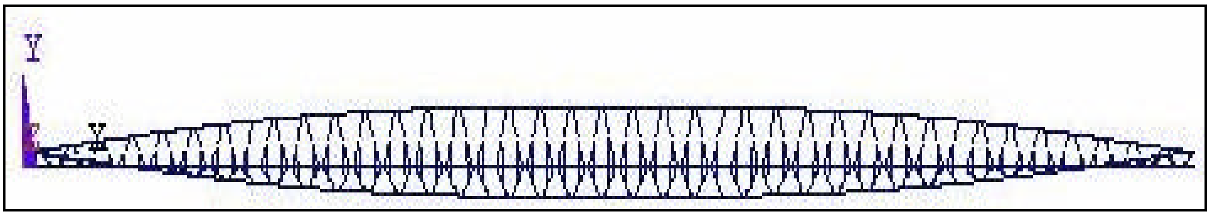
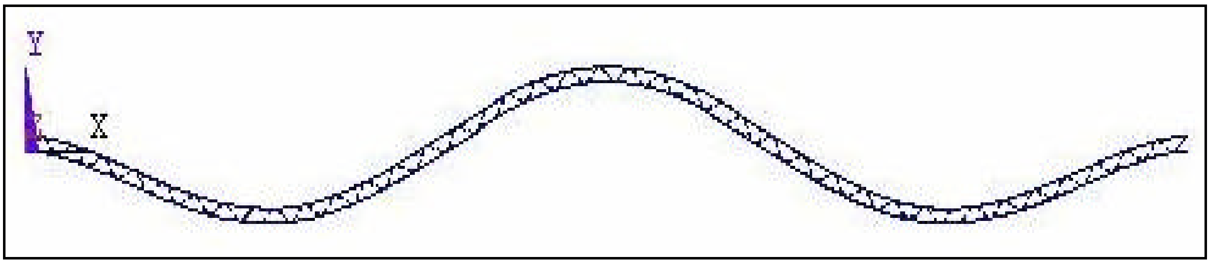


(5)

Figure 8-(1) to (5) Mode shapes 1 to 5 of the 30 m gantry.



(6)



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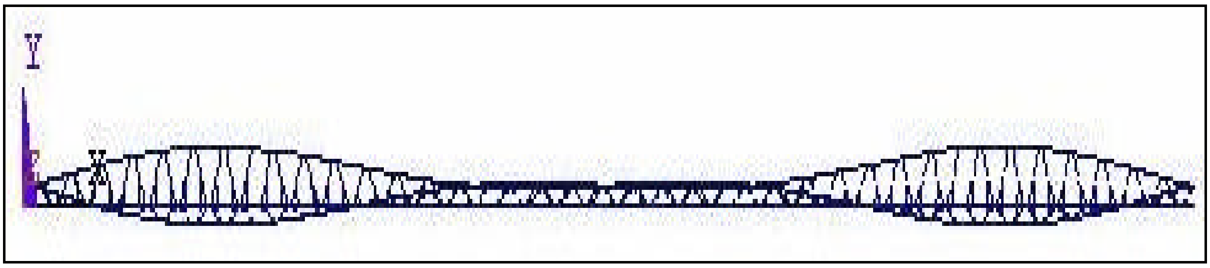

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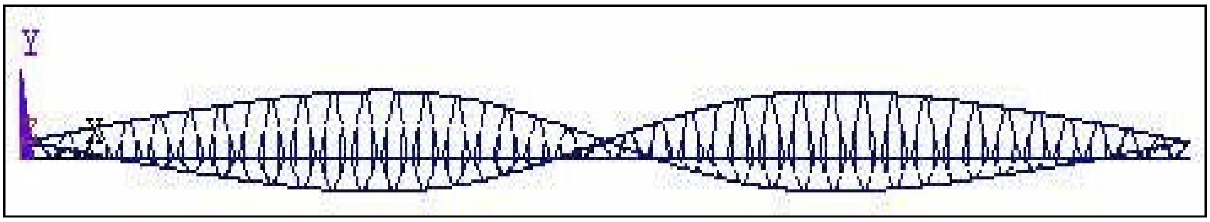

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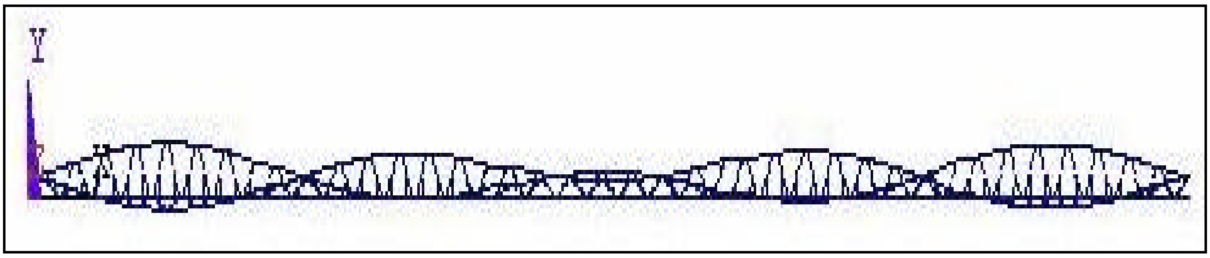

(10)

Figure 8-(6) to (10)　Mode shapes 6 to 10 of the 30 m gantry.