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Structural Design of Large-Span Single Layer Latticed Dome

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Summary

This report describes the types and effects of imperfections which will affect the strength of a large-scale steel single-layer latticed dome, by taking the case of designing and constructing a single-layer latticed dome as large as approx. 190 m in plane diameter.
We have conducted extensive analyses on the buckling strength, vibration characteristics, construction method and so on in consideration of imperfect loads and imperfections in order to realize a large-scale single-layer latticed dome which has been rarely built.
This report describes the following effects:
1) How imperfections affect the buckling strength and/or member stresses of a roof; and
2) The causes and amplitudes of the under-construction imperfections, and how they affect the roof stresses.

1. Outline of Roof Structure

The building dealt with in this report is "Nagoya Dome" constructed in Nagoya City, Japan. This building is a multi-purpose stadium with steel roof, mainly used for baseball games. The construction of the building was commenced in August, 1994 and completed in March, 1997. (Photo 1-1)
The roof, located at the height of approx. 36 m above the ground level, covers the ball park with the seating capacity of approx. 40 thousand. It is as large as approx. 29,000 m^2 in area and has an approx. 5,000 m^2 glass rooflight at the center.
The structural type of the roof is a steel single-layer latticed dome, 187.2 m in plane diameter and 32.95 m in height, which is one of the largest single-layer latticed dome structures in the world. (Fig. 1-1)
The under-roof structure is a steel framed reinforced concrete structure, which is 36 m high. The diameter on centers of columns along the outermost circumference is 229.6 m, and the diameter on column centers of the top floor is 187.2 m. The tension rings for the roof are located on the girders, each of which over-hangs 1.8 m inward from the center of column on the top floor of the under-roof structure because applied was the lift-up method in which the roof was built on the ground and hung up for the purpose of rationalizing the construction method. Therefore, the roof's plane diameter on centers of the tension ring members is 183.6 m, and the roof height on centers of the members is 32.95 m. Thus the rise-to-span ratio (H/L) is 0.179. (Fig. 1-2)
Each lattice component of the roof consists of 4 triangles approx. 10 m per side each, produced by splitting a triangular plane approx. 20 m per side. Those triangles are rigidly jointed to each other by welding them at the points of contact.
The lattice is made of steel pipes, 650 mm in diameter, the thickness of which is gradually increased from 19 mm at the roof center to 28 mm along the outer circumference. For the tension rings, steel pipes 950 mm in diameter and 50 mm in thickness are used. (Fig. 1-3)

2. How Geometrical Imperfections Affect Single-Layer Latticed Dome Strength

The typical structural type of the large-scale steel structure domes which have been constructed is multiple truss. Some of the reasons in designing them are as follows:

1) The out-of-plane stiffness of single-layer roofs is as small as 1/10 – 1/30 compared with that of multiple-layer roofs, and their buckling strength is likely to be largely affected by geometrical imperfections.
2) Though it is predicted that the imperfections affect others as well as the buckling strength of a single-layer latticed dome, their amplitudes and the degrees of their effects are unclear.
3) It is predicted that the geometrical imperfections occur under construction. Since the causes and amplitudes of imperfections are unclear, the effects of imperfections shall be conservatively evaluated in designing a real structure, which will require the assumption of larger geometrical imperfections and result in smaller design strength of a single-layer latticed roof.

This chapter describes the result of comparative study on how the amplitudes of geometrical imperfections affect the elastic limit strength and buckling strength of the steel single-layer lattices under the different load conditions. We evaluate buckling strengths and elastic-plastic strengths in consideration of various imperfections; The analysis model was a three-dimensional model with 577 nodal points and each nodal point was provided with 6 degrees of freedom. Non-linear incremental analysis was applied for any analyses by considering the characteristics of a single-layer latticed structure, except for seismic time history response analysis. The main frame under the roof was replaced by equivalent springs in the model.
The analytical results are shown in Figs. 2-1 to 2-3.

The analytical results are summarized as follows:
1) The elastic limit loads were approx. 1/3 to 1/2 of the global buckling loads, and the ultimate loads were approx. 1/2. Therefore, the member yield precedes the global buckling on such a scale as the single-layer latticed dome used in analyses.
2) The effects that geometrical imperfections exercised on buckling loads were the largest during the full load application: the strength accounted for approx. 60 % at the imperfection $\xi \fallingdotseq 1.0$ and reduced to approx. 47% at the imperfection $\xi \fallingdotseq 2.0$.
3) The perfect system buckling load with the partial load considered at the center of the roof was the smallest: 76% of that during the full load application. The effects of the imperfections were relatively small. Near the imperfection $\xi \fallingdotseq 2.0$ in any load distribution, the buckling strength was approx. 1/2 of that during the full load application.
4) The effects that imperfections exercised on the ultimate strength were relatively small: approx. 92 % at the imperfection $\xi \fallingdotseq 1.0$.
5) The effects that imperfections exercised on the elastic limit strength at the imperfection $\xi \fallingdotseq 2.0$ varied to 85% $\sim$ 65% of the perfect system, which shows the result of the effects exercised by the combination of load distribution and imperfection distribution.

The above listed results show that the geometrical imperfections affect the member stresses and the member strength as well as the global buckling strength. They also shows that the effects greatly differ depending on the pattern of imperfection distribution.
To rationally realize a large-scale single-layer latticed dome, the amplitudes and distribution of the imperfections used for conservative evaluation shall be precisely defined. The next chapter describes the distribution and amplitudes of the imperfections which occur during the construction of a real structure as well as their effects.

3. Evaluation on Imperfections of Steel Single-Layer Latticed Dome

This chapter presents the types and amplitudes of the imperfections which occur at a steel single-layer latticed dome under construction, and the degrees of their effects, all of which are found in analyses.
The under-construction conditions taken into consideration were
1) (erection analysis) · · ·the assembling procedure / temporary structure support conditions, and the load conditions;
2) (temperature analysis) · · ·the local temperature variation under construction; and
3) (welding analysis)· · ·the variation in the effects of the members' axial shrinkages caused by the assembly welding, during the period of assembling the steel lattice for the roof on the site.

The above listed analyses 1) to 3) were individually conducted, and their results were accumulated to define the effects.
Specifically, the typical under-construction configurations during the roof fabrication were set in the analytical models. The analysis in consideration of the above conditions 1) to 3) was conducted on each of the set models, the results of which were calculated in the addition, and thus the predicted effects of the construction were grasped.
The imperfections accompanying the construction are shown by the differences between the member stresses / contact deformations calculated in the above method and the results obtained in the method (perfect system analysis) where all the loads were applied together to the perfect system model usually used for the structural analysis. Photo 3-1 shows the construction in progress, and Fig. 3-1 shows the sketch of the analytical models.
The results of expressing the effects of the construction in the variation correlative distributions of the member stress ratios are shown in Figs. 3-2 to 3-5.
The abscissa indicates the perfect-system analytical results, and the ordinate indicates the under-construction imperfection analytical results.
Figs. 3-6 and 3-7 show the distributions of the vertical imperfections at the points of contact. Fig. 3-6 shows the plane distribution of geometrical imperfections, while Fig. 3-7 shows the imperfections graphed by nondimensionalizing the geometrical imperfections at the radius of gyration of the members and splitting them into 6 between the center and the outer circumference of the roof.

The summary of the results is as follows:
1) Most of the imperfections which occur under on-site erection are caused by welding.
2) The effects of the whole construction result in the member stress ratio of approx. ±0.2.
3) The effects on the member stresses under the different analytical conditions vary from one another in amplitude and affected member. Therefore, the effects of the whole construction are smaller than the result of the simple accumulation of the analytical results.
4) The geometrical imperfections under construction are as small as approx. 0.15 i (i = radius of gyration of the member) in case of the nondimensionalized imperfections.

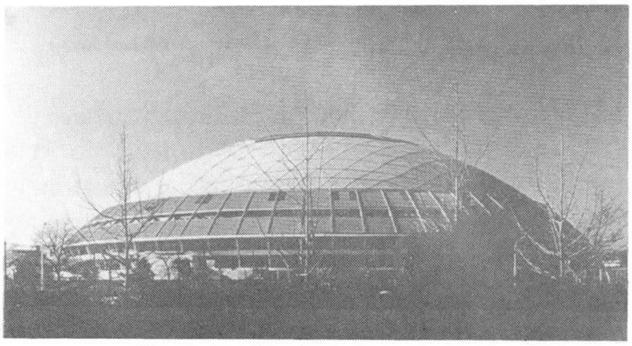
The effects that construction exercised on a single-layer latticed dome resulted in larger imperfections of member stresses and rather smaller geometrical imperfections. It is also concluded that the member stress imperfections were mainly caused by the bending moment variation.

The similar analyses were conducted on the various under-construction conditions which were changed from the original ones. The degree of effects increased by approx. 50 %, but there was no great difference in the tendency of effects.

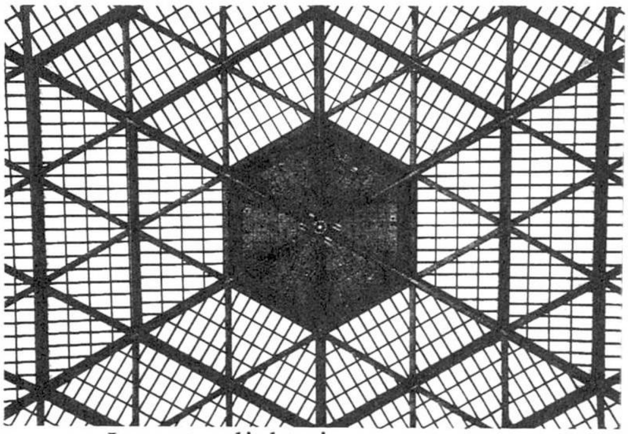
4. Conclusion

The measurement of member stress variations started during the construction. The propriety of the analyses has been verified in comparison between the analytical results of under-construction imperfections and the actual measurements. The analytical results are in good agreement with the results of actual measurements, which means that the imperfections of a large-scale single-layer latticed dome can be grasped to some degree in analyses. Therefore, the conservative evaluation where the effects of imperfections are rationally considered is available in designing a large-scale single-layer latticed dome.

Lastly, here by taking this opportunity, I would like to express my gratitude to Professor Yamada of Tohoku University, Professor Hangai of Tokyo University, and many other people concerned for their kind cooperation and guidance in this research.



Panoramic view



Inner top-light view

Photo 1-1 Panoramic view of Nagoya Dome

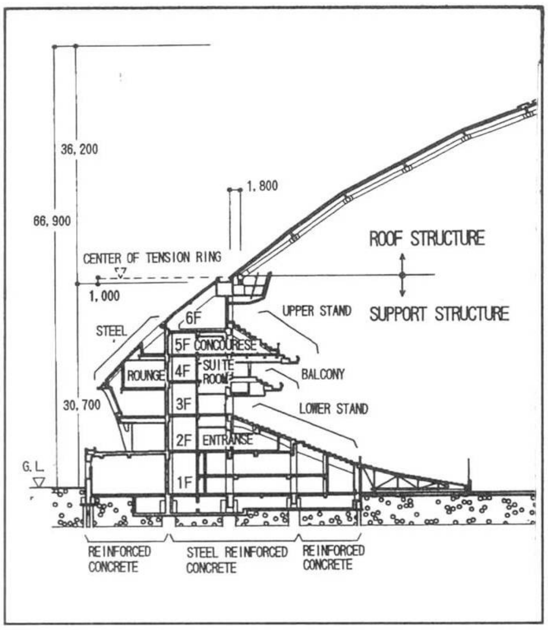


Fig. 1-1 Section of the building frame

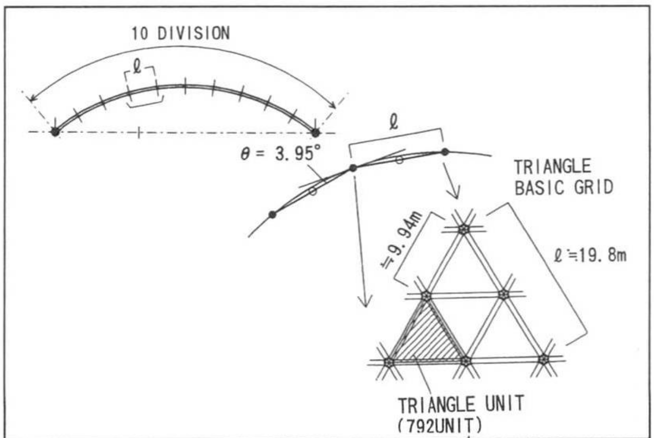


Fig. 1-2 The lattice division pattern

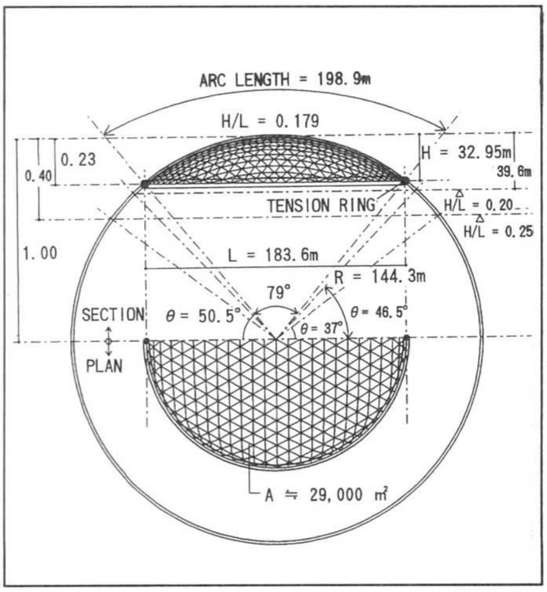


Fig 1-3 The roof Structure section

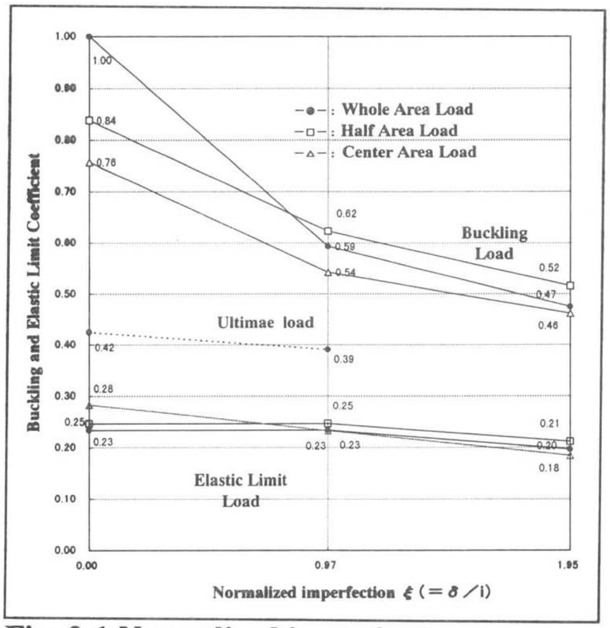


Fig. 2-1 Normalized imperfection amplitude and buckling coefficient

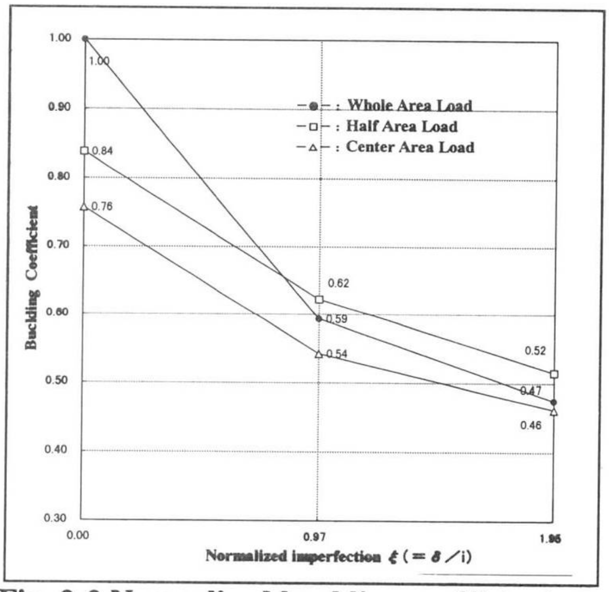


Fig. 2-2 Normalized buckling coefficient

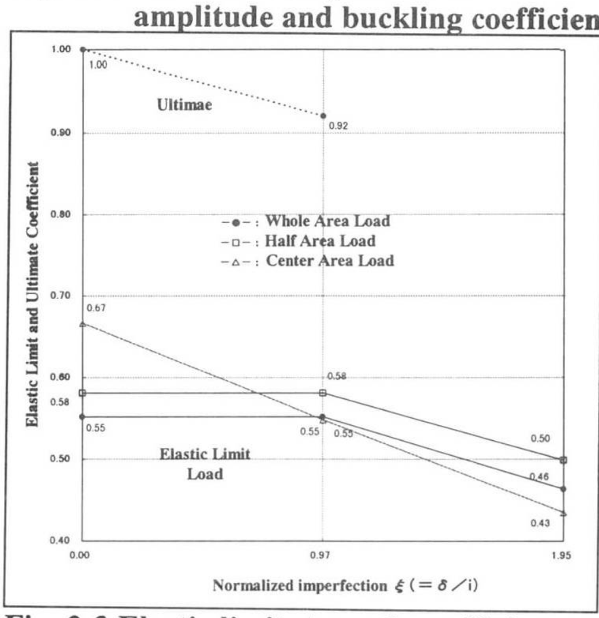


Fig. 2-3 Elastic limit strength coefficient

Photo. 3-1 Over view of construction state

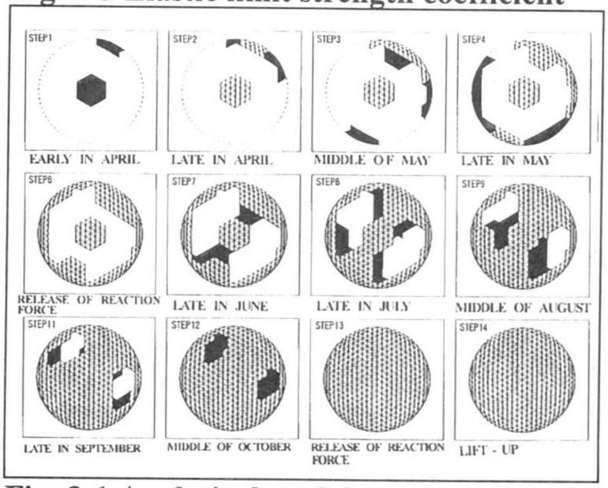


Fig. 3-1 Analytical models corresponding to construction steps

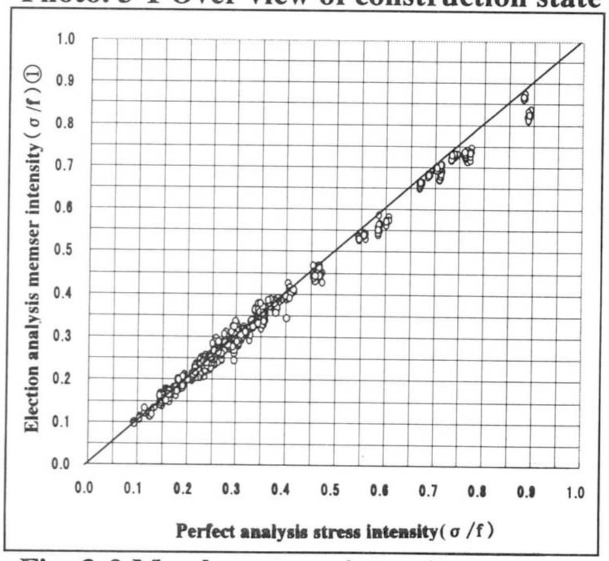


Fig. 3-2 Member stress intensity correlation (Erection analysis)

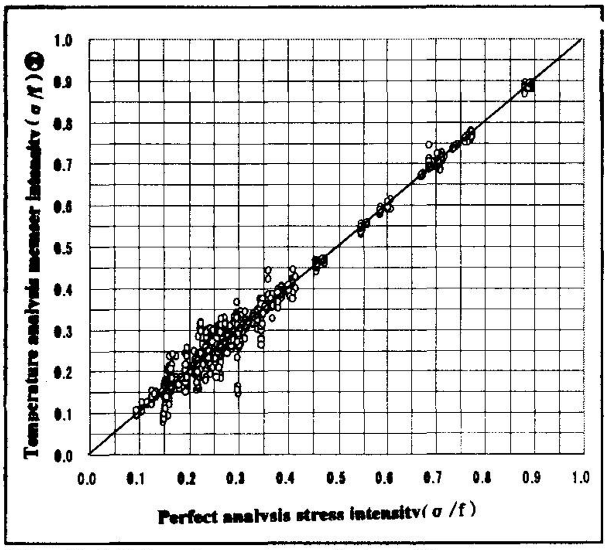


Fig. 3-3 Member stress intensity correlation (Temperature analysis)

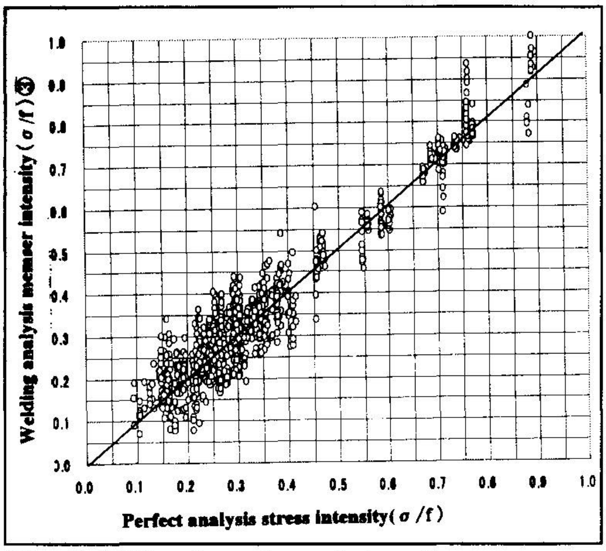


Fig. 3-4 Member stress intensity correlation (Welding analysis)

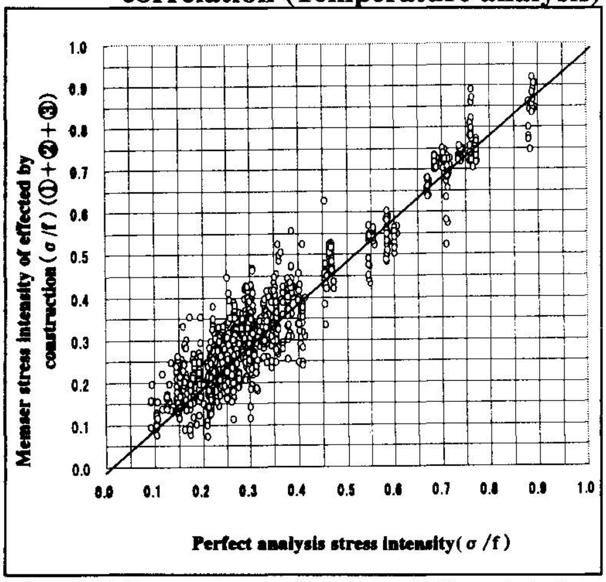


Fig. 3-5 Stress intensity correlation total (under-construction)

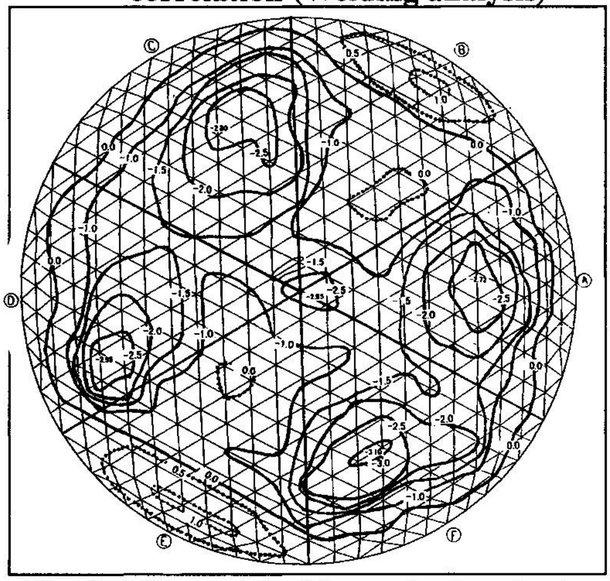


Fig. 3-6 Geometrical imperfections(cm) (plane distribution)

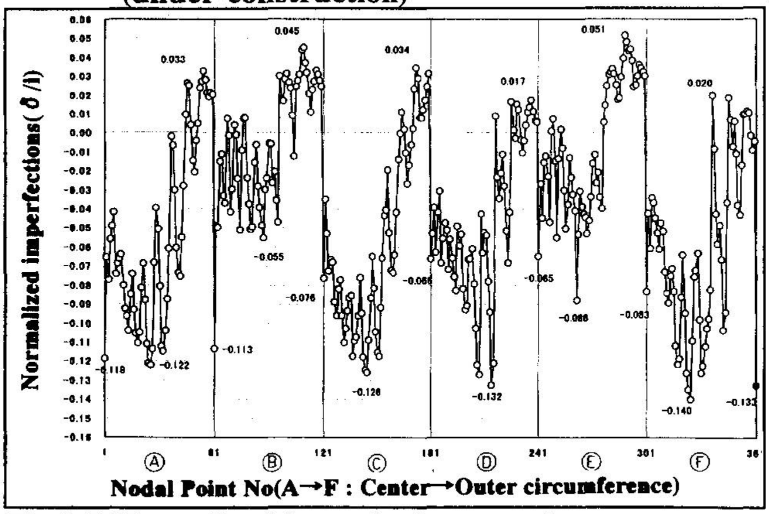


Fig.3-7 Normalized imperfections graph of each nodal point

reference

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