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Structural design of a continuum of reinforced concrete elements

~ Realization of "Rias-Hall",Ofunato public hall&library in Japan ~

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Abstract
"Ofunato" is a Japanese local city faced with Pacific Ocean and representative ria-coastline in Japan. This small city is known for its picturesque scenery of a nature rock named "Anatoosi-iso"(at Goisi-kaigan) formed of slate rock and which is a symbol of this city.
Architect Chiaki Arai designed a new landmark architecture named "Rias-Hall" in Ofunato (Fig.1&2), and the motif of this archtecture is "Anatoosi-iso".
The main structural material of "Rias-Hall" is reinforced concrete (RC) and its unique space/form made by the vernacular landscape.
This paper reports the character and the process of structural design of "Rias-Hall".

Keywords: continuum of reinforced concrete, folded plate RC wall, flying buttress

1. Introduction
On the one hand, the main structure of japanese reinforced concrete construction is rigid frame with beam elements and column elements, because the one of the japanese traditional architecture was wooden frame in recent years. On the other hand, it seems that reinforced concrete has been used not as line element but as massive element in Europe, because the begining of architecture was masonry construction.

Intrinsically the reinforced concrete is plastic material and the continuous structure can be composed of it by processing the formwork. To create the plane surface with little ruggedness more than line, it can be avoided thah the stress concentrates into those points and that the variety of the construction quality, for example placing of reinforcement and concrete casting. Therefore it seems to be suitable for the material character that it is composed not as line but as plane surface in view of the original character of reinforced concrete. The possibility of the reinforced concrete structure with plane surface is pursued paying attention to the advantage of it in this design of this hall.

This paper contains how to compose this hall of the plane surface with reinforced concrete and how to varify this structure.

Fig.1: Outside view of Rias-Hall

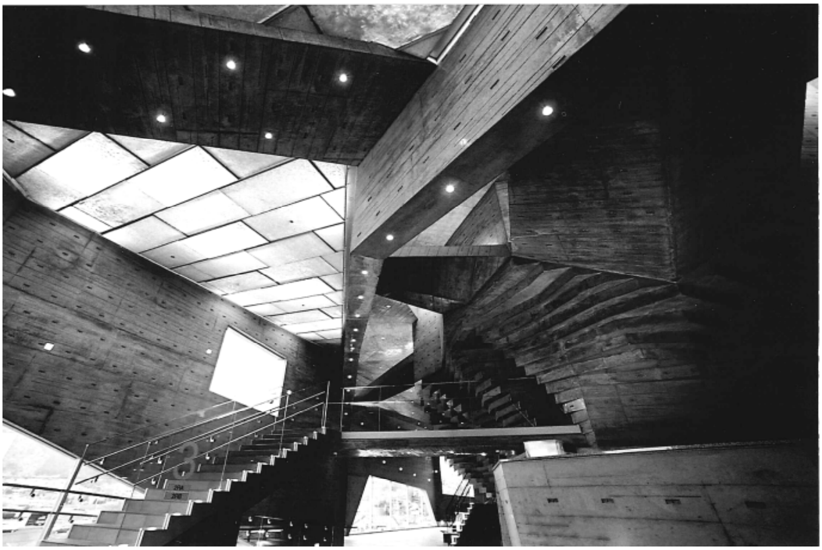


Fig. 2: Inside view of Rias-Hall

2. Design Concept **Locality of Ofunato, Japan**

It is usual to adopt the structure of reinforced concrete with high rigidity and shielding effectiveness for the environmental demand performance such as interception, insulation and earthquake resistance that hall architecture is often required. Moreover, it is requested the cost condition for public buildings and the simple construction method to be able to build with local constructors. Then this project was started as cast-in-place reinforced concrete because of those above demands.

Ofunato, where this Rias-Hall, is a Japanese local city faced with Pacific Ocean and representative ria-coastline in Japan in which ria shoreline hall is located (Fig.3). This small city is known for its picturesque scenery of a nature rock named “Anatoosi-iso (Fig.4)" (at Goisi-kaigan (Fig.5)) formed of slate rock (Fig.6) and which is a symbol of this city.

Fig.3: Ria coastline of Ofunato

Fig.4: “Goishi-kaigan”, Ofunato,
Erosion sculpted the rock into its unique form

Fig.5: “Goishi-kaigan”, Ofunato

Fig.6: Slate-rock,
widely distributed in Ofunato

The form of the hall was composed of a gradual curve at the beginning of this design (Fig.7). However Architect Chiaki ARAI reviewed the motif of the external design to adapt to the locality of Ofunato during the workshop with the citizens of it. The external image like natural rock, Anatoosi-iso, in Ofunato ria-coast was checked again, because the folded plate in polyhedron was suited it more than sphere and the sphere form was expensive to construct. Finally it decided to design the external polyhedron form with folded plates (Fig.8).

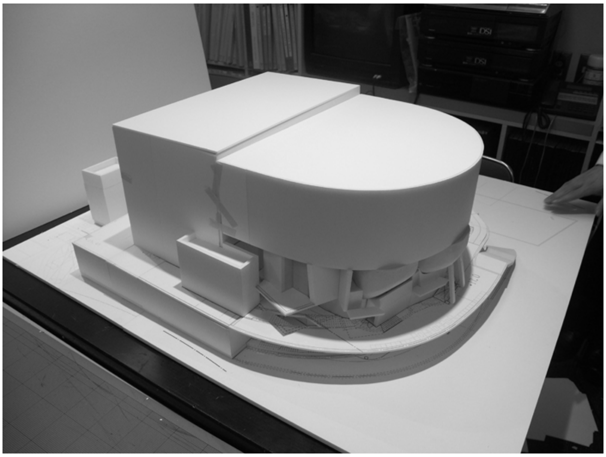


Fig.7: First study model

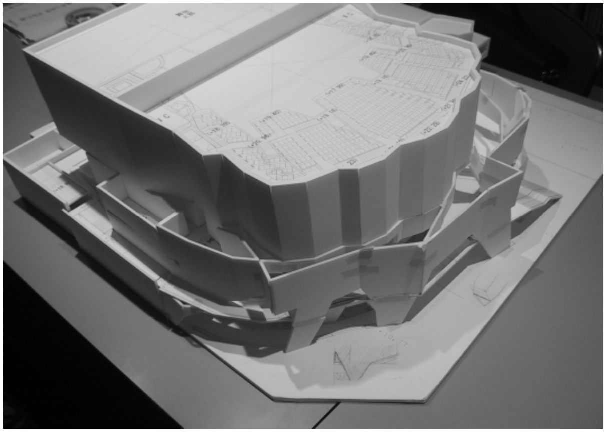


Fig.8: Final study model

3. Study of structure

3.1. Basic Concept

Rias-Hall is the complex facility consisted of three zones, which are hall zone, library zone and service zone. In hall zone there are the hall which composed of 1100 audience seats and the stage for musical concert (Fig.9), and foyer and restaurant around it (Fig.10&11). There are dressing rooms and equipment rooms in service zone. The basic concept of structural design is the composition of structural elements not to disturb each others and each space. Those points to create the structural elements for each demand performances are as follows:

1. In hall zone each space are arranged to fold. Especially the audience seats are put out to foyer and restaurant side, because the amount of the upper audience seats is required in advance. Therefore the bottom of the audience seats appears as an inner skin inclined to outside when it is looked up from foyer side. Also it is folded plate of polyhedron according to arrangement of the upper audience seats divided three parts. The outer skin on out side of foyer consists of folded plates. It is possible to get comfortable space not to disturb other one, because the inner skin and outer one are composed as structure. At the same time, it is important to study how to bear this upper audience seats.

Fig.9: Audience seats of the hall

Fig.11: Reataurant of the hall zone

Fig.10: Foyer of the hall zone

2. The demand performance of service zone is to create the reasonable, practical and simple frame. Then the form is hexahedron basically and the structure is flat plate of it (Fig.12).

Fig.12: Service zone outside view

3. Library has the wall-girders connected with upper walls on same plane to get large continuous space with unifying reference room (Fig.13).

Fig.13: Library reference room

3.2. Study of Structural frame

～From "how to bear the audience seats" to "how to bear with audience seats～

At first the audience seats on the second floor could be formed three independent bowls with two columns in each one (Fig.14). However, the bearing system was considered again because the columns were interfered with the foyer and that form didn't match the organic image like ria-coastline. Chiaki ARAI, Architect, had an image for the internal seats like the forward part of a ship.

It seems that there were some rules to design the structure of the ship though it can be complicated seemingly. Is it really possible to support the upper structure of the hall by the audience seats? In other words, the structure can be that the audience seats unify with the roof of the hall.

Then this structure was considered the semi-monocoque composed of frames and plates by regarding it as a body of ship, especially hall roof as upper deck and folded plate walls as outside plates (Fig.15).

Generally it is necessary to design as Cantilever beam the radial frames in the pit under the audience seats for air condition. Here when these radial frames were extended until outside of the hall and support the upper structure of the hall, it seemed that the inner load on the frames counterbalances the outer one. If these radial frames worked like the rib of the ship, it could be supported the upper structure. The enough thickness and height were designed not only for normal force but also for bending and shear stress, because the ducts penetrated through these frames.

These rib frames were supported to connect with folded plate walls which were designed like concentric circle as the wall between hall and foyer. Therefore the folded plate walls worked as the keel-girders for radial frames. Automatically it could be stabilized by two points where each frame intersected with the folded plate walls. These folded plate walls were the element to resist against the force with high rigidity like an arch rather than a beam because they had some bulged opening. They transfered the load of the normal force to the foundation.

3.3. Flying-buttress on the foyer

On the one hand, the traditional flying buttress is transfered the thrust on the vault roof for the long-term load. On the other hand, these flying butresses (Fig.16), which were connected between the inner skin and the outer skin on the upper side of foyer, not only was transfered parts of the stress to outside by the weight hall roof, but also was secured unifying between inner and outer on the earthquake particulary. Therefore these had the flat V-form sections, because these were needed not only the rigidity of the normal stress, but also the horizontal one for bending shear

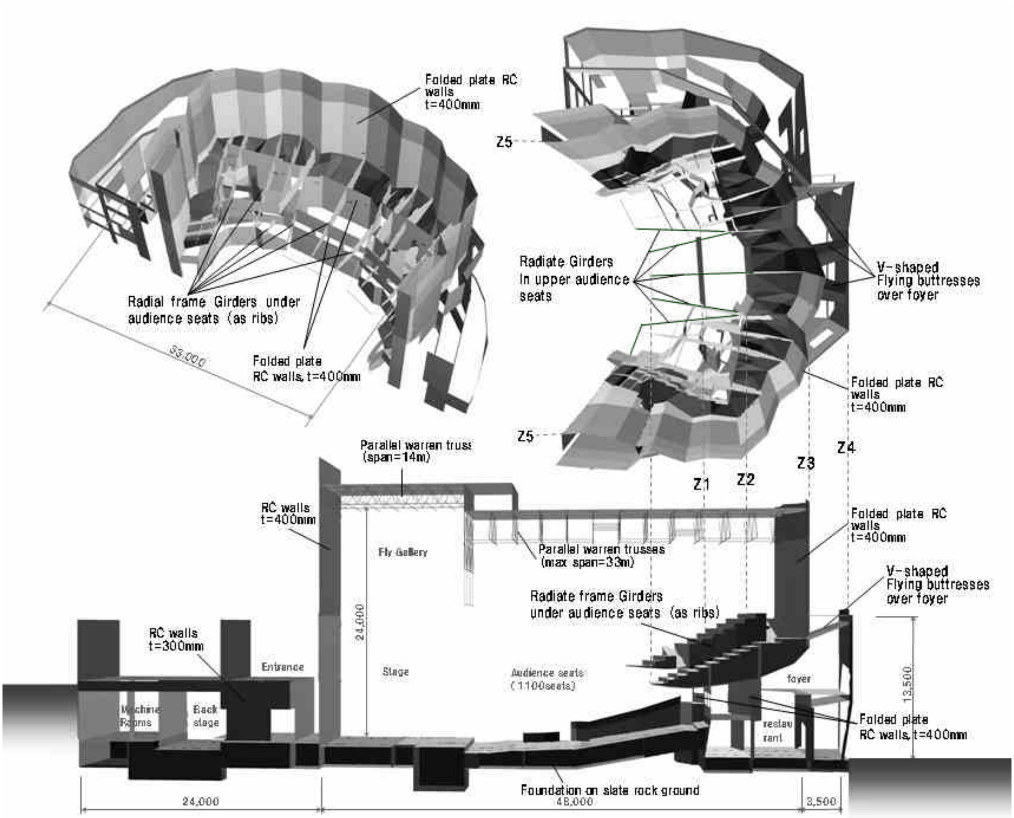


Fig.15: Structural Diagram of Rias-hall

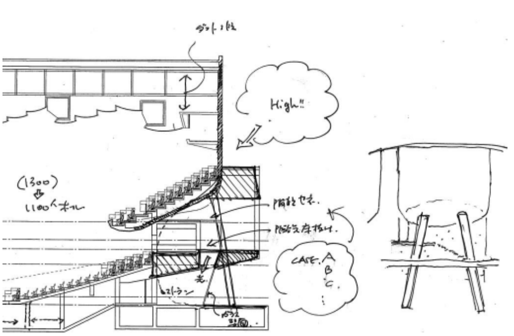


Fig.14: Fisrt structural sketch

Fig.16: Flying buttress on the foyer

3.4. Library – continuous reference room

The wall-girder, whose height is the one of a layer, was continued on the same plane to the one of studio and multiple space on the upper floor, because it can be got large continuous space with unifying reference room. In the other words, the continuous wall-girder were designed from lower floor to upper floor. Threrfore it can be designed the minimum amounts of columns in reference room by wall girder.

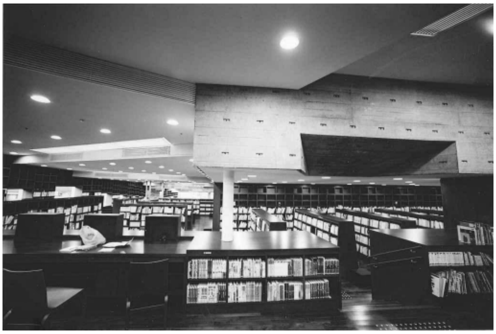


Fig.17: Library,
continuous reference room

3.5. To solve complicated form, to design flat thick wall

The method of structural design was based on Japanese seismic codes and AIJ standard[1],[2], therefore we conducted two structural analysis. One is a FEM liner analysis and another is a beam element model of non-linear analysis.

1. FEM linear analysis

   The analysis of this complicated form was executed with the 3D model using FEM analysis programm (MSC/Nastran) (Fig.18&19).

   The more the plan and section were changed influenced by the workshop with citizens, the more the study model, scale 1:50, was transformed. Therefore it proceeded in each sections at the same time that the verification of the analysis model made by this study model was reflected to architectural design and service design.

2. Non-linear analysis

   Besides FEM linear analysis, the pushover analysis with simplified flame model was made. In this hall, the ultimate capacity which it was necessary was set when the value of the ductility reduction factor (Ds) of Japanese seismic codes was 0.55.

   The ultimate capacity was set when the beams between surface elements were broken with shear stress partially. However it was confirmed that the one at this time exceeded the demand capacity of Japanese seismic codes (Fig.20).

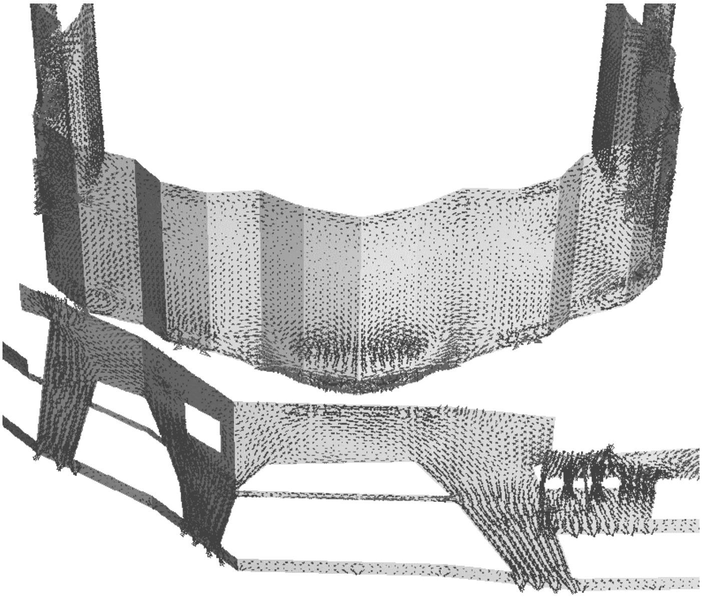


Fig.18: FEM result,
Major & minor principle stress of Folded plate RC walls

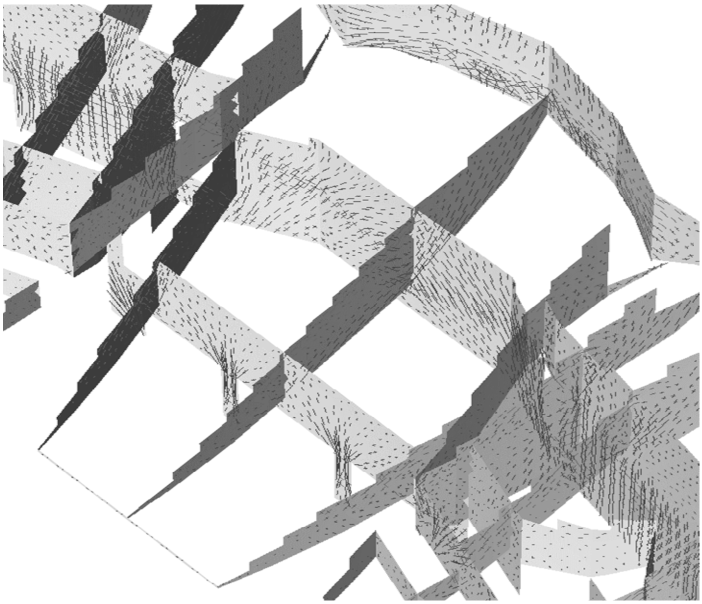
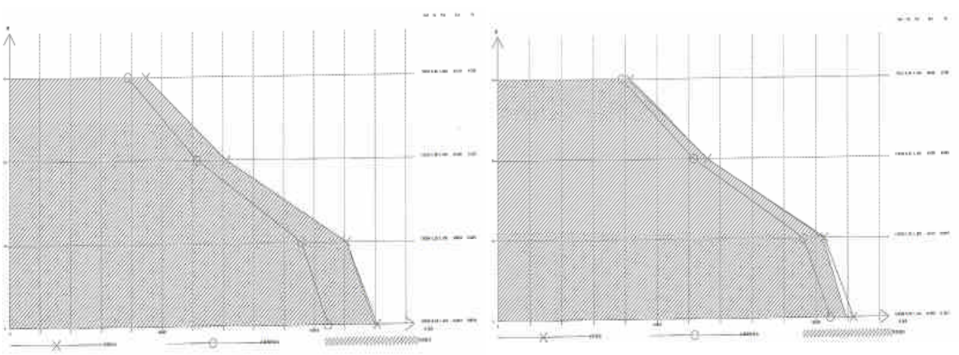


Fig.19: FEM result,
Major & minor principle stress of radial girders
under audience seats



X direction　　　　Y direction

Fig.20 Ultimate capacity of Rias-hall
(Ds factor= 0.55)

4. Construction

Rias-Hall was planned with cast-in-place concrete, which is highly-popularized construction method in Japan. And the skeleton was constructed by local rebar workers and formworkers (Fig.22～23).

To get untroubled layout of reinforcement and to enable enough concrete fill, Rias-hall was constructed of uniform 30～40cm thickness walls.

Especially, under construction, temporary supports under the hall and library, which were at 1st floor level, were kept by the time the strength of the upper concrete reached to the designed value (Fig.21).

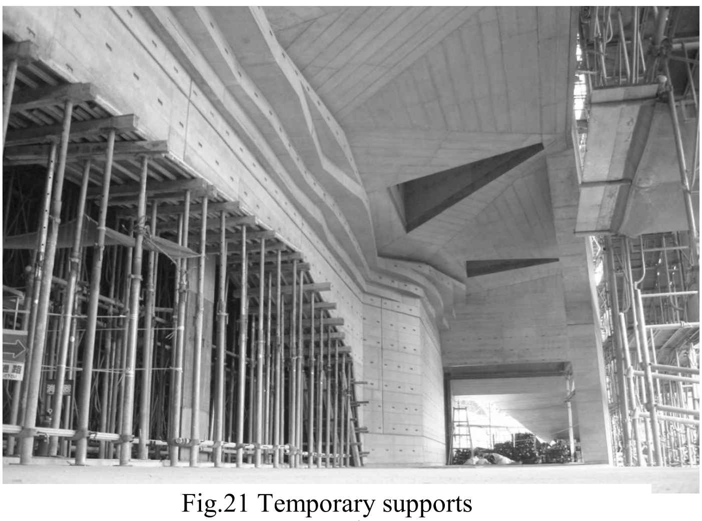


Fig.21 Temporary supports
under the hall, 1^{st} floor level

Fig.22 Formwork of the audience seat and radial girders

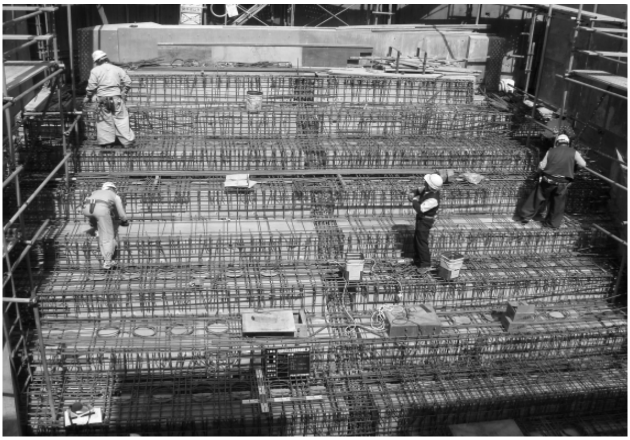


Fig.23 Reinforcement of the audience seats and girders

Acknowledgement

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References

[1] Architectual Institute of Japan, Standard for Structural Calculation of Reinforced Concrete Structures -Based on Allowable Stress Concept- , 1999

[2] Architectual Institute of Japan, Ultimate Strength and Deformation Capacity Buildings in Seismic Design , 1990