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FEASIBILITY ASSESSMENT OF ULTRA-HIGH-PERFORMANCE-CONCRETE APPLICATION TO NPPs

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ABSTRACT

In order to further improve the safety level of nuclear power plants (NPPs), external hazards such as earthquake, tsunami, tornado, forest fire, aircraft impact, etc. were added to safety evaluation of NPPs. As such, it is necessary to improve the structural integrity of reactor buildings against external hazards. The feasibility assessment result was presented with regard to the effectiveness of ultra-high-performance-concretes (or UHPCs) application to NPP reactor buildings.

INTRODUCTION

In order to further improve the safety level of nuclear power plants (NPPs), external hazards such as earthquake, tsunami, tornado, forest fire, aircraft impact, etc. were added for the safety evaluation. To address the above issues, a research project was carried out to improve the structural integrity of the building by applying ultra-heigh-performance concretes (or UHPCs), etc., to NPP building. The feasibility assessment of applying UHPCs to reactor buildings is discussed in this paper.

OUTLINE OF THE PROJECT

The project "Development of technical infrastructure for upgrading materials, structures and construction methods of nuclear power plant buildings" was carried out from 2015 to 2019 to improve the structural integrity of the building and to realize an economical facility by reducing the amount of material by applying ultra-heigh-performance concretes (or UHPCs), etc., to the nuclear facility building. The outline of this project is describe in figure 1.

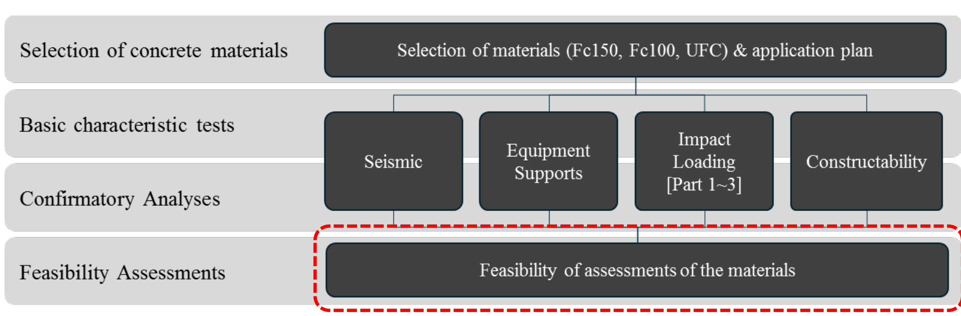

Figure 1. Outline of the project.

FEASIBILITY ASSESSMENT PROCEDURE

The feasibility of applying ultra-high-performance concretes is pursued for both Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) reactor buildings. In order to evaluate the effectiveness, the following two cases of application are assumed.

- Case-A: Only normal concrete (Fc 33 ~ 45 N/mm^2) is applied to reactor buildings in a conventional manner
- Case-B: In addition to normal concrete, ultra-high-performance concretes (UHPCs) and heavyweight concrete are applied to the specified critical members of reactor buildings, to cope with external hazards

As the conclusion, four cases of buildings are evaluated for this assessment (see Table 1)

Table 1: Four types of reactor buildings for assessment.

Reactor	Case-A Only normal concrete applied	Case-B Normal concrete, UHPCs and heavyweight concrete applied
PWR	Conventional PWR	UHPC PWR
BWR	Conventional BWR	UHPC BWR

The feasibility of the UHPCs application is evaluated by comparing the four cases of buildings (Table 1) from several aspects. The evaluation procedure is described below:

- Selection of ultra-high-performance concretes (UHPCs) and development of their application plan including heavyweight concrete
- Calculation of required building member thickness for external hazards
- Estimation of building material quantities (i.e., concrete, rebar)
- Evaluation from the viewpoint of safety, construction cost, and construction duration
- Feasibility assessment of ultra-high-performance concretes application to reactor buildings

SELECTION OF ULTRA-HIGH-PERFORMANCE CONCRETES AND DEVELOPMENT OF THEIR APPLICATION PLAN INCLUDING HEAVYWEIGHT CONCRETE

The following ultra-high-performance-concretes (UHPCs) and heavyweight concrete are selected and applied to the critical members of the reactor buildings.

- Fc150 (Fc 150N/mm^2): Fc150 ultra-high-performance-concrete containing steel fiber and polypropylene fiber has approximately 4.5 times higher compressive strength than normal concrete and has high ductility due to steel fiber contained therein. Fc150 is used with rebar as reinforced concrete (RC). Fc150 is applied to outer walls of reactor buildings including prestressed containment vessel (PCCV) of PWR, as it is expected to improve the structural integrity against impact forces such as aircraft impact.

- UFC (Fc 180N/mm^2): Ultra-high-performance steel fiber reinforced concrete (UFC) has approximately 5.5 times higher compressive strength than normal concrete and has high ductility due to steel fiber contained therein. UFC is used as a composite member with RC (See Figure 2). UFC is applied to roof slabs, as it is expected to improve the structural integrity against impact forces such as aircraft impact.

- Fc100 (Fc 100N/mm^2): Fc100 ultra-high-strength-concrete containing polypropylene fiber has 3 times higher compression strength than normal concrete and has fire resistance performance due to polypropylene fiber contained therein. Fc100 is applied to inner shear walls and slabs, as it is expected to improve the seismic capacity of buildings.

- Heavyweight concrete (Fc 33 - 60N/mm^2): Heavyweight concrete has approximately 1.6 times higher density than normal concrete. Heavyweight concrete is applied to radiation shielding walls, as it is expected to minimize the required wall thicknesses.

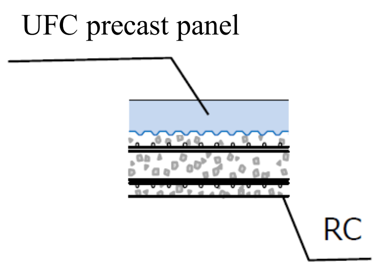

Figure 2. UFC composite member.

The selected UHPCs, explained above, are applied to both PWR and BWR reactor buildings, namely UHPC PWR, UHPC BWR respectively, as depicted in Figure 3.

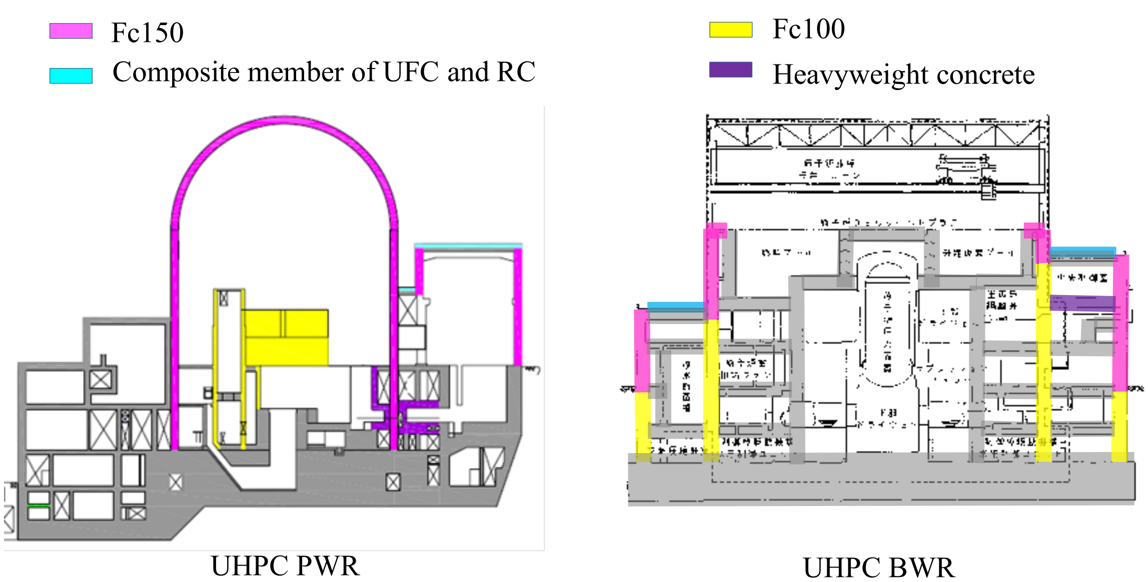

Figure 3. Application of ultra-high-performance concretes to reactor buildings.

CALCULATION OF REQUIRED BUILDING MEMBER THICKNESS FOR EXTERNAL HAZARDS

With respect to Fc150, Fc100 and UFC, multiple tests were carried out to obtain necessary data for building seismic and impact analyses. Seismic and aircraft impact analyses including FEM analyses are conducted for the four cases of reactor buildings shown in Table 1, and the required building member sizes and rebar amounts are calculated respectively.

As the result of structural analyses, it was confirmed that the required member thicknesses of the ultra-high-performance-concretes (UHPCs) (i.e., Fc150, Fc100 and Composite member of UFC and RC) can be reduced by approximately 30% compared with normal concrete RC. This is because UHPCs and UFC-RC composite have higher compressive strength and ductility than normal concrete (i.e., Fc 33 ~ 45 N/mm^2).

ESTIMATION OF BUILDING MATERIAL QUANTITIES

The required concrete and rebar quantities in the reactor buildings were calculated based on seismic analyses results (see Table 2). The application of UHPCs resulted in reduction of both the building member (e.g., walls) thicknesses and the required building footprint (see Table 3), thereby leading to the reduction of the building material quantities. It is noted that minimized building footprint is likely to contribute to the ease of plot plan and construction management.

Table 2: Required building material quantity.

Reactor	Material	Ratio (/Case-A)	
		Case-A Only normal concrete applied	Case-B Normal concrete, UHPCs and heavyweight concrete applied
PWR	Concrete	1.00	0.85
	Rebar	1.00	0.87
BWR	Concrete	1.00	0.84
	Rebar	1.00	0.83

Table 3: Required building footprint.

Reactor	Ratio (/Case-A)	
	Case-A Only normal concrete applied	Case-B Normal concrete, UHPCs and heavyweight concrete applied
PWR	1.00	0.91
BWR	1.00	0.91

EVALUATION FROM THE VIEWPOINT OF SAFETY, CONSTRUCTION COST, AND CONSTRUCTION DURATION

Safety

The effectiveness of the ultra-high-performance-concretes (UHPCs) application to the reactor buildings is summarized as below:

- With respect to impact forces such as aircraft impact, it was confirmed that Fc150 and UFC (i.e., the composite member with RC) application is highly effective. That is because of their higher compressive strength and ductility due to contained steel fibers.
- Fc100 application was confirmed to be highly effective for seismic force. That is because of higher compressive strength.
- As for fire-resistance performance, Fc100 and Fc150 were confirmed to be equivalent to normal concrete RC (i.e., Fc 33 ~ 45 N/mm^2) because of the effect of polypropylene fibers.
- As for radiation shielding, heavyweight concrete was confirmed to be effective because of its high density.

As for the structural safety of reactor building, the evaluation results are summarized as below:

- UHPCs applied buildings can withstand the same level of hazard loads with thinner building members than normal concrete applied buildings. If normal RC member is required to be extraordinary thick to withstand external hazards, the thickness of the member using UHPC can be optimized for feasible design and construction.
- The use of UHPCs leads to optimization of the building walls thickness, thereby reducing the building's seismic load because of the building dead weight reduced. It is especially effective to apply UHPCs to the upper parts of buildings to effectively minimize seismic force.
- It is possible to secure greater safety margins for structurally important building members with UHPCs. Even if the external hazard conditions are enhanced during the plant lifetime, major renovations to the building may be avoided because of the safety margins. The safety of the buildings will be ensured in the longer term.
- The accumulation of the UHPCs experimental data may result in better structural performances such as high ductility, that will lead to more effective design of buildings.

Construction cost and construction duration

The construction costs of the four types of reactor buildings (see Table 1) were calculated based on the material cost and construction related cost such as rebar arrangement and concrete placing, and construction durations were estimated as well (see Table 4). It is noted that other costs including heavy components and piping were not considered in this assessment.

When UHPCs are applied to the reactor buildings, the construction costs of the buildings are almost the same or slightly higher than the conventional reactor buildings. This is because the unit costs of HPCs are more expensive than normal concrete, though building material quantities were reduced as explained in the last section.

Besides, it is found that the construction duration of the UHPCs applied PWR building is shortened by about three months due to decreases in concrete and rebar quantities (see Table 2). On the other hand, it is found that the construction duration of the UHPCs applied BWR building is almost the same as the conventional BWR buildings, as the UHPCs applied members are not on the critical path of the construction sequence. It should be noted that the estimated construction durations were calculated excluding the followings, and the effect of the UHPCs application can be underestimated in this assessment:

- Cost reduction from minimized building scale with respect to external building finishing and temporary construction efforts
- Decrease in excavation volume, site development, etc. due to reduction of building footprint
- Reduction of the bulk materials for mechanical and electrical items such as piping, cables, etc.
- Reduction of on-site management costs by shortening construction duration, economic benefits from early start-up of plant operation, etc.

Table 4: Construction cost and duration.

Reactor	Construction cost		Construction duration	
	Case-A Only normal concrete applied	Case-B Normal concrete, UHPCs and heavyweight concrete applied	Case-A Only normal concrete applied	Case-B Normal concrete, UHPCs and heavyweight concrete applied
PWR	1.00	1.03	—	-3 months
BWR	1.00	1.08	—	±0 months

FEASIBILITY ASSESSMENT OF ULTRA-HIGH-PERFORMANCE CONCRETES APPLICATION TO REACTOR BUILDINGS

Feasibility was assessed in consideration of the estimated construction cost, construction duration, and the analyses results against external hazards.

As shown in Table 5, the application of the ultra-high-performance concretes (UHPCs) to both PWR and BWR buildings is considered to be effective.

Table 5: Feasibility assessment result.

Reactor	Evaluation			Feasibility assessment result
	Safety	Construction cost	Construction duration	
PWR	Effective	Same	Effective	Effective
BWR	Effective	Slightly negative	Same	Effective

The economic efficiency is evaluated to be slightly negative, highly depending on the high unit costs of UHPCs. However, the construction cost is expected to improve in the future considering the followings:

- Several aspects were not considered in the construction costs as described in the last section.
- The costs of UHPCs are expected to decline in the future due to growing use and technological advances. If the UHPCs cost is reduced by about 30%, the increase in the construction costs can be offset.

In the case of applying UHPCs to an existing plant building, UHPCs can be used to reinforce building members in locations with severe spatial constraints. As a result, it is expected that impacts on the existing mechanical and electrical equipment can be minimized.

CONCLUSION

Feasibility of ultra-high-performance concretes (UHPCs) application to reactor buildings was assessed. Compared with the reactor buildings using normal concrete, the buildings using UHPCs leads to better structural integrity of the buildings and reduce the building material quantities (i.e., concrete, rebar) by approximately 15%. As the results, the construction duration is expected to be shortened by up to 3 months and the cost increases are estimated by 3 to 8%. However, the cost evaluation is based only on concrete and rebar related to costs, excluding others, the UHPC unit costs is expected to decline in the future. In summary, the application of UHPCs is considered to be effective for both PWR and BWR reactor buildings.

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