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CORDINATION OF STRUCTURAL AND SYSTEM SAFETY MEASURES FOR BEYOND DESIGN BASIS EVENTS

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ABSTRACT

In the nuclear field, structural measures are applied only to prevent failure from design basis events, while mitigating failure consequence of beyond design basis events based on defence in depth is considered as the domain of system safety measures. And the philosophies and methods are separate between structural and system safety measures.

Risk reduction measures that rely on preventing failure lead to limitless reinforcement with excessive margins against high uncertainty events, such as beyond design basis events and natural hazards. Preventive measures are approaching their technological limits. For this reason, there is a need for rational risk reduction methods that emphasize mitigating consequence of events with high uncertainty.

The final goal of this research is to develop a method for evaluating the mitigation performance that can be expected even after structural failure has occurred, and to develop rational risk reduction methodologies and technologies that emphasize consequence mitigation by incorporating (linking) the failure mitigation performance of structural measures into risk assessments and system safety measures.

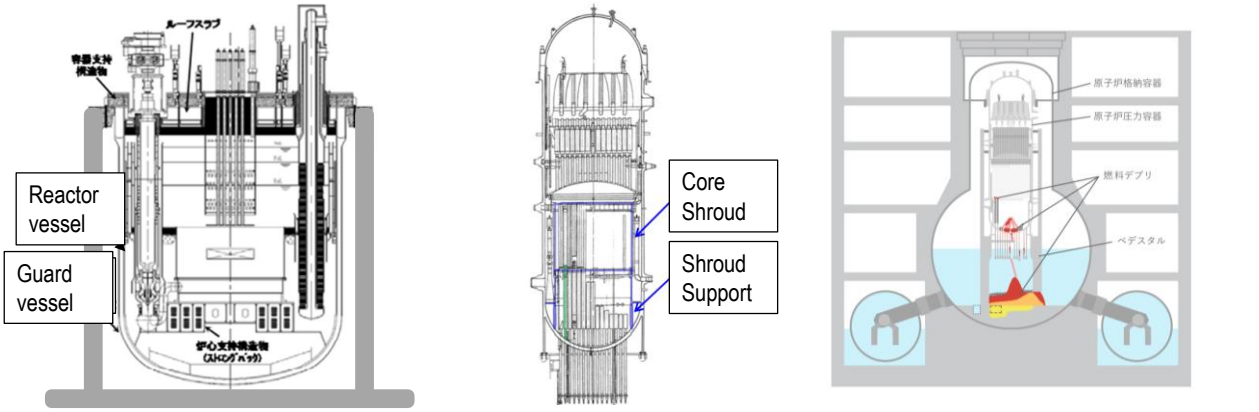
INTRODUCTION

Problems for Large Uncertainty Events (ex. Beyond Design Basis Events, Natural hazards)

Failure preventions based only on assumed loads and scenarios are difficult for large uncertainty events. Unreasonable prevention measures lead to endless reinforcement and strict inspections due to large margins. Preventive measures are approaching their technological limits.

Mitigation measures based on the concept of defence in depth (IAEA, 2016) is effective for large uncertainty events. However, current mitigation measures relay on system safety, and structural measures have few contributions. For this reason, there is a possibility that the system safety measures will be based on extreme hypothetical failures that differ from the actual behaviours.

Figure 1 shows examples of large uncertainty problems. (a) is uncertainty regarding reactor vessel buckling and following heat removal under excessive earthquake. It leads to requirement for 3D seismic isolation, thickening of reactor vessel, and additional decay heat removal system. (b) is uncertainty regarding the initiation and propagation of SCC cracks in shrouds. It requires high frequency inspection for all welds, that results in reduced operating rate. (c) is the Fukushima-daiichi-nuclear plant, where the reactor vessel support structure has already been damaged. Requirements for reinforcement of entire building and protections against large displacement of the reactor vessel are discussing against excessive earthquake



(a) Beyond design events of next-generation fast reactors

(b) Light water reactor internals during earthquakes

(c) Damaged light water reactors (1F)during earthquakes.

Figure 1. Examples of large uncertainty problems.

Structural Measures & System Safety Measures

In the nuclear field, structural measures and system safety measures have different philosophies, methods and applicable area as Table 1 and Table 2. Structural measures are applied only to prevent failure from design basis events (DBE), while mitigating failure consequence caused by beyond design basis events (BDBE)based on defence in depth is considered as the domain of system safety measures.

"Structural Measures" and "System Safety Measures" have few collaborations.

Table 1: Measures for design basis events (DBE).

	Structural Measures	System Safety Measures
Objective	**Failure prevention of individual component**	**Maintenance of system safety performance**
Method	**Comparison of conservative analysis results with allowable failure criteria for assumed failure modes**	**Maintenance of system safety performance**

Table 2: Measures for beyond design basis events (BDBE: Large Uncertainty).

	Structural Measures	System Safety Measures
Objective	**None**	**Maintenance of system safety performance and mitigation of accident consequence**
Method	**None**	**Risk informed and performance base approach Portable devices, Accident management, Passive safety**

PROPOSALS OF CORRDINATED MEASURES FOR BEYOND DESIGN BASIS EVENTS (LARGE UNCERTAINTY EVENTS)

Different approach for rational risk reduction between DBE and BDBE

Risk curve can be plotted on the plane between probability P and consequent damage C as in Figure.2. Effective approaches to reduce risk are different between DBE and BDBE (Kasahara et.al. 2017). Prevention approach is rational for DBE, therefore conventional measures for DBE are adequate. However, mitigation approach is rational for BDBE and large uncertainty events.

New structural strength approach is necessary for mitigation of failure consequence. Furthermore, coordination between structure and system safety measures are expected for rational risk reduction as Figure 3 (Kasahara et.al. 2024).

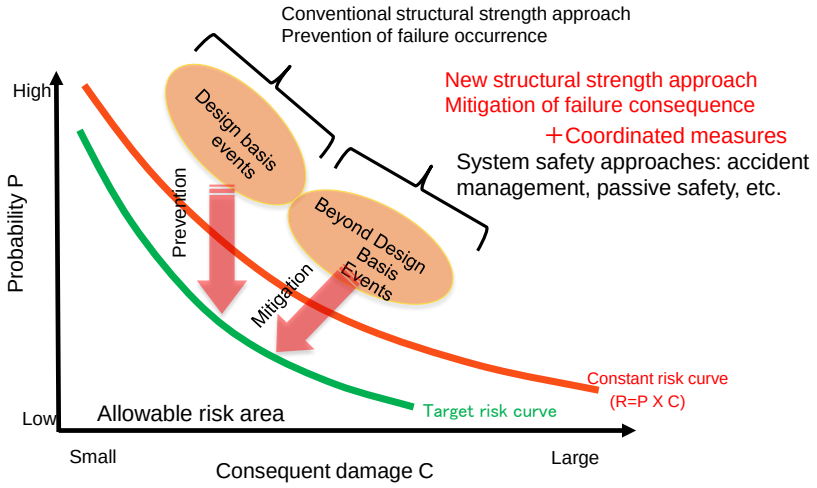


Figure 2. Different measures for DBE and BDBE.

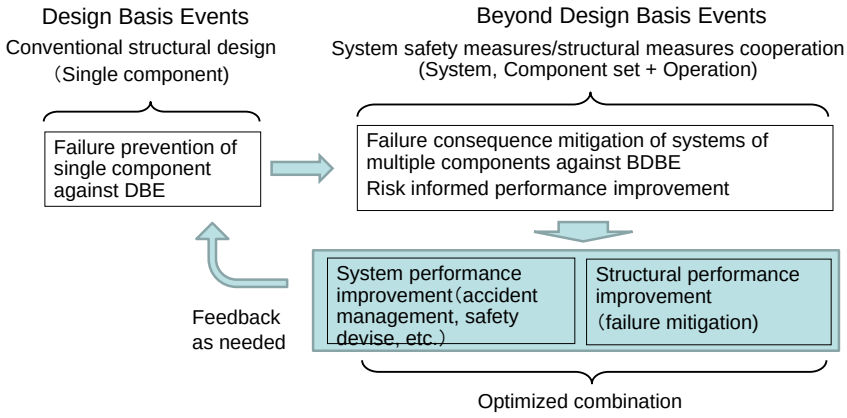


Figure 3. Coordination framework of structural measures and system safety measures

STRUCTURAL PERFORMANCE ACCORDING TO FAILURE SEQUENCE

Failure sequence of structures

Figure 4 shows typical Failure sequence of vessel and piping structures. Failure modes progress according to loadings. Required performances for DBE are both serviceability and safety. Therefore, any failure modes should be prevented for DBE. On the other hand, required performance for BDBE is safety and failure modes which have small impacts on safety could be allowed as Figure 4.

It is future theme to clarify what structural performance is for BDBE. Development of performance evaluation method based on the prediction (best estimate) of the failure sequence from the initiation to a catastrophic state is also future issue.

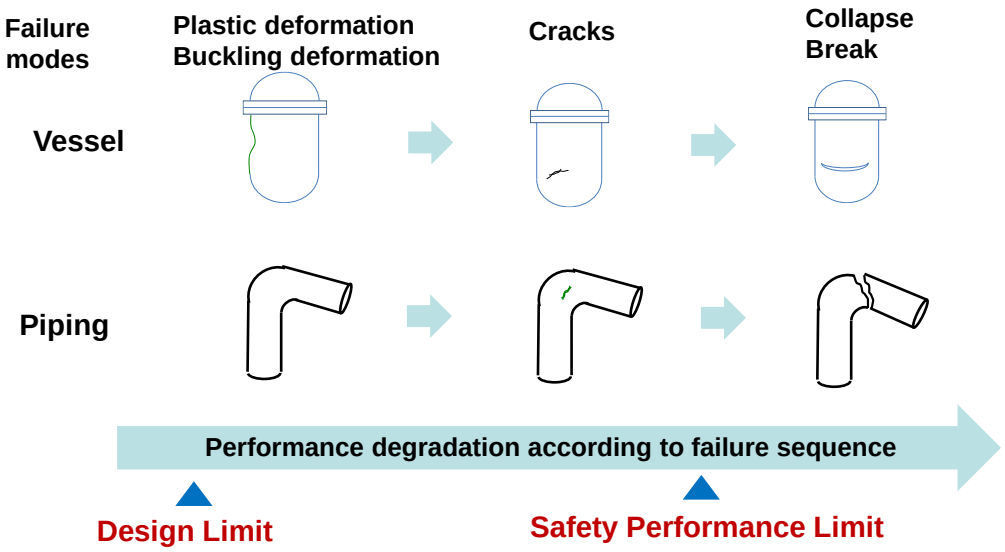


Figure 4. Failure sequence of individual component.

PASSIVE SAFETY STRUCTURES WITHOUT CATASTROFIC FAILURE

Definition of passive safety structures

Passive safety structures reduce the load and energy by preceding a failure mode (deformation, small crack, etc.) that has a small impact on safety, and mitigate consequence to such catastrophic failure modes as collapse, break and so on, etc., those lead to lose of safety functions (Kasahara et.al. 2024).

In this study, passive safety structure is defined as a structure that maintains safety functions based on natural phenomena without external power or operation.

Natural reduction in load or force by preceding failure with a small impact on the safety function, prevent catastrophic failure leading to loss of function. Preceding failure may suppress or promote catastrophic failure, and passive safety is established in the former case. Figure 5 shows the simple example of passive safety structures without catastrophic failure.

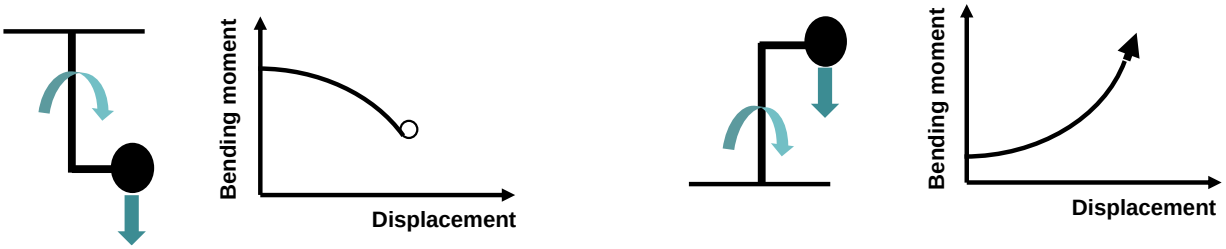


Figure 5 Simple example of passive safety structures without catastrophic failure

Failure sequence of thin vessels under vibration tests (Passive safety)

As Figure 6, buckling tests were performed applying horizontal vibration load to carbon steel thin cylindrical shells, simulating fast reactor vessel by reducing dimension (Kasahara, 2016). The phots and response acceleration of the test specimens (before and after buckling) are shown in Figure 7 (Hasegawa et. Al., 2022). It was observed that after buckling, response acceleration drastically reduced and post-buckling behavior became stable. Its mechanism was analyzed that the natural frequency decreases and falls below the input frequency after buckling, resulting in a phase delay and anti-phase, and energy is less likely to be input from the shaking table (Yiji et.al., 2024). Thus, the shape is stable without excessive deformation. The author named its characteristics as “the passive safety structures without catastrophic failure”.

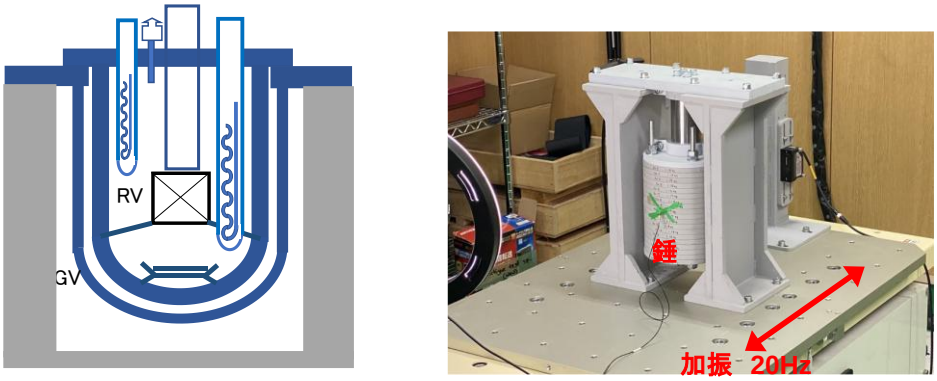


Figure 6 Experimental apparatus s of reactor vessel model under vibration

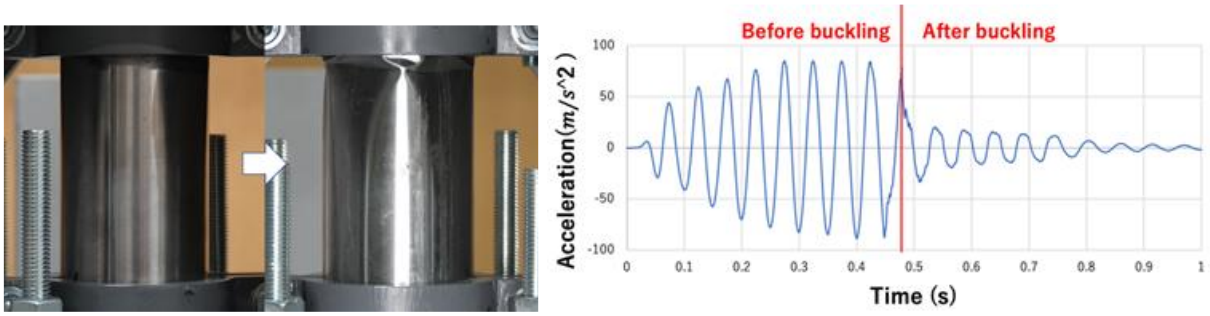
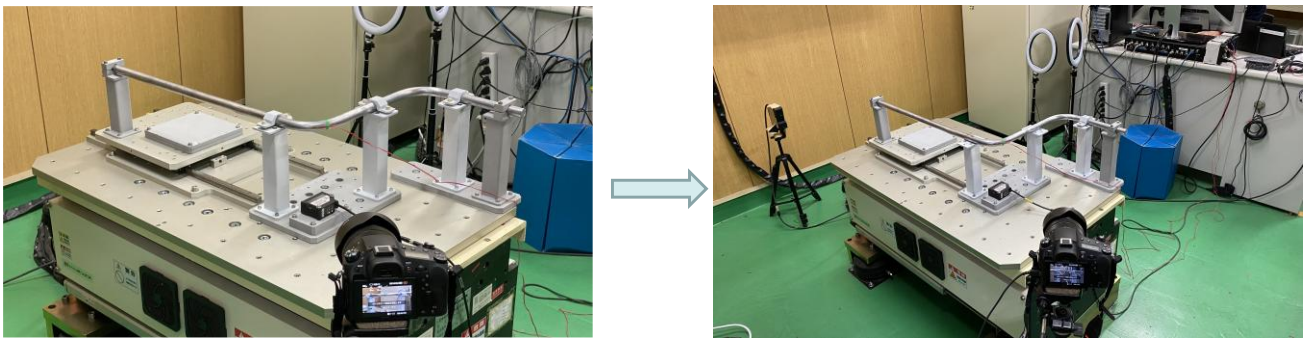


Figure 7 Experiments to ensure stability of cylinder after buckling under vibration

Failure sequence of a set of pipe and support structures under vibration tests (Passive safety)

Piping systems consist of pipes and their support. Rigidity of piping against earthquake is usually realized by multiple supports. Passive safety characteristics of piping system was experimentally demonstrated (Horinouchi et.al. 2024). Piping system with 3 supports were tested by shaking table as Figure 8. 2 supports broke by vibration as the right photo of Figure 8. The maximum acceleration response decreased after two support breaks (Figure 9). However, 3rd support did not break and there were no collapse and break of pipe itself even though acceleration increased. Adobe mechanism was clarified that, 1st support break decrease the natural frequency piping system toward input frequency and induce the 2nd support break. After 2 support break, natural frequency of the system became lower than input frequency (The right figure of Figure 9), resulting in a phase delay and anti-phase, and energy is less likely to be input from the shaking table. Therefore 3rd support and pipe itself did not fail, even though input acceleration increases.

Larger scale experiments were conducted on the piping system with plural supports under seismic loadings (Nakamura and Kasahara, 2024). Similar results were obtained. Above results show the passive safety characteristics in the piping system.



Initial piping system with 3 supports **1 support after 2 support break**

Figure 8 Experiments to ensure stability of piping system after support failure under vibration

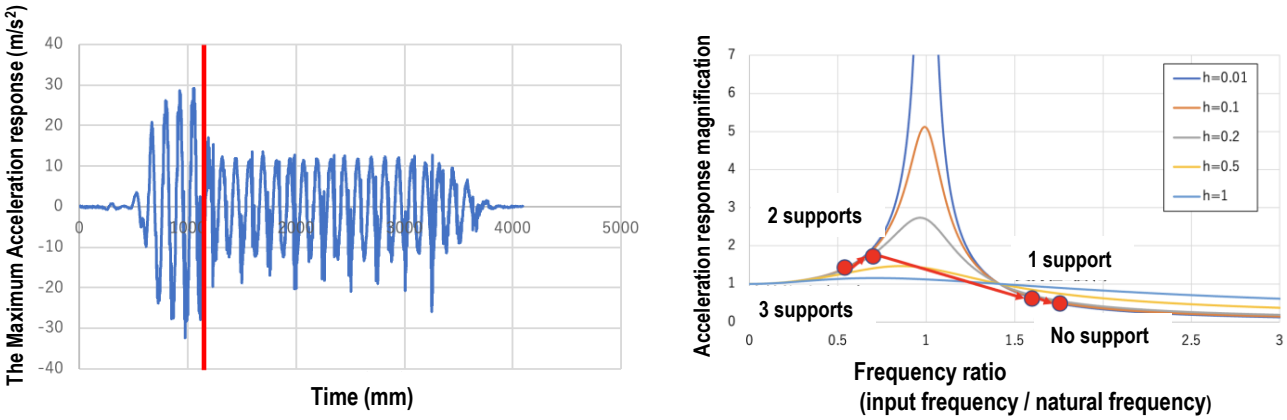


Figure 9 Experiments to ensure stability of piping system after support failure under vibration

SYSTEM SAFETY CONSIDERING STRUCTURAL PERFORMANCE

Passive safety structures hardly progress their frailer modes into catastrophic stat as Figure 10. It means that passive safety structures have high performance to extend safety margin and time margin. By incorporating above structural performance, system safety measures for BDBE and large uncertainly events become effective as Table 3. For examples, large time margin enables various kinds of accident management.

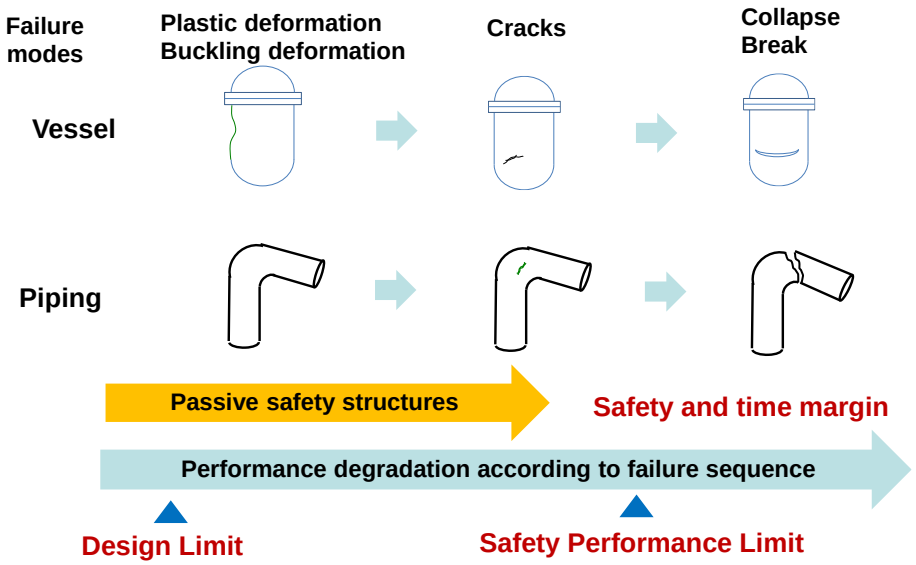


Figure 10. Failure sequence of passive safety structures.

Table 3: Coordinated measures for beyond design based events (Large Uncertainty).

	Structural Measures	System Safety Measures
	Coordinated measures between structure and system safety	
Object	Mitigation of failure consequence of component set (suppressing the spread of damage)	Mitigation of systems and mechanisms to prevent large-scale releases of radioactive material
Method	Mitigation performance evaluation based on failure sequence prediction (best estimate), performance improvement (use of passive safety structures, etc.)	System safety measures that utilize safety margins and time margins resulting from the impact mitigation effects of structural measures

CONCLUSION

Mitigation approach is rational to reduce risks against BDBE and large uncertainty events. Conventional structural measures are applied only to prevent failure from design basis events, while mitigating failure consequence is considered as the domain of system safety measures.

Therefore, the author proposes the extension of structural measures from prevention to mitigation. One of idea is utilization of passive safety characteristics in structures. They enjoy large safety margin and time margin until loss of safety functions.

The final goal of this research is to develop a method for evaluating the mitigation performance that can be expected even after structural failure has occurred, and to develop rational risk reduction methodologies and technologies that emphasize consequence mitigation by incorporating (linking) the failure mitigation performance of structural measures into risk assessments and system safety measures.

Future challenges

To realize the above goal, the following research issues are planned.

・Methodology for linking structural and safety measures
・Expanding the scope from individual component to component set
・Prediction of failure sequence from the initiation to a catastrophic state
・Evaluation of safety performance according to failure sequence
・Coordination by incorporating structural performance (ex. safety margin, time margin) into risk assessments and system safety measures

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