

## **APPLICATION OF FRACTURE CONTROL TO NUCLEAR COMPONENTS FOR MITIGATION OF ACCIDENT CONSEQUENCE**

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### **ABSTRACT**

As the lessons learned from the Fukushima nuclear power plant accident, mitigation of accident consequence for Beyond Design Basis Events (BDBE) become important. Authors propose application of fracture control concept for mitigation of accident consequence of nuclear plants as contribution from structure and material fields. In the case of reactor vessels under high temperature and pressure conditions, small cracks from local failure will release internal pressure and can avoid a large scale ductile fracture of general portions. For piping under excessive earthquake, ratchet deformation and crack initiation consume vibration energy and can prevent collapse and break of pipe wall. Strength of pipe supports can be designed lower than pipe itself. Controlled break of support leads to plastic deformation without the break. Thus, large scale and catastrophic failures can be avoided by energy release due to prior small scale failure.

### **INTRODUCTION**

As the lessons learned from the Fukushima nuclear power plant accident, countermeasure for Beyond Design Basis Events (BDBE) become important (Hatamura 2014, IAEA 2015). Trend of risk ( $R$ ) is generally described by the product of probability ( $P$ ) and consequent damage ( $C$ ) as shown in figure 1.

Efficiencies of risk reduction approach are different for risk stages as shown in the figure1.

Therefore, multi-stage countermeasures become suitable according to performance per resources (Takada, 2016).

In the case of high probability and small consequent damage, the reduction of probability by the failure prevention is efficient. This is design area. On the other hand, efficient approach for the case of low probability and large consequent damage is the reduction of consequent damage. It is evacuation area. Beyond Design Basis Events (BDBE) exist their intermediate and correspond to the accident management area.

According to Defence in Depth concept, this intermediate area is categorized the 4<sup>th</sup> layer and different approaches are required from the design categorized lower layer (IAEA 2016, Canadian Standard 2016).

However, previous efforts in the structural strength fields focused on design area. There are few activities and are no suitable approaches for beyond design area.

Therefore, there exists the large gap between design area and beyond design area in structural strength fields. Events for considering to structure strength are severe accidents and severe natural hazards such as excessive earthquake. Above events are defined as Beyond Design Basis Events (BDBE).

Objective of this study is proposal of mitigation approach for BDBE in the structural strength field.

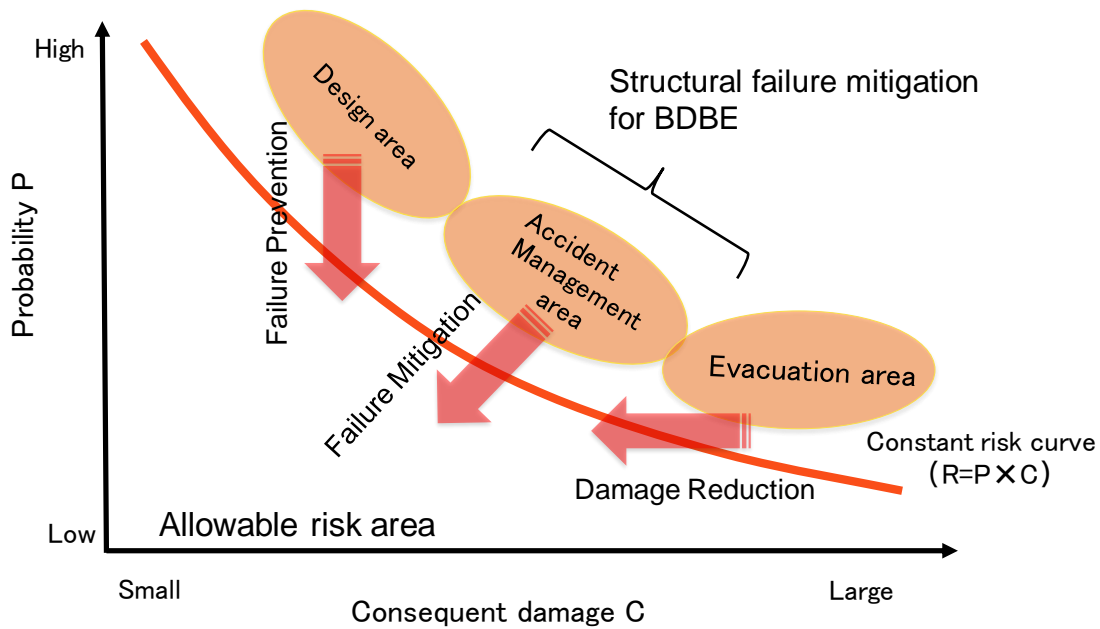


Figure 1. Risk reduction scheme based on continuous approach.

## FAILURE MITIGATION FOR BDBE IN STRUCTURAL STRENGTH FIELD

Structural strength is generally defined as strength to satisfy required performance. Requirements and required function are different between DBE and BDBE as in Table 1.

Requirements for Design Basis Events (DBE) are safety, availability and serviceability, therefore any failure should be prevented.

Requirements for BDBE are safety and resilience, therefore failure consequence should be mitigated.

Performance and related failure modes are different according to requirements. Under DBE, any failure modes including stable and unstable failure modes should be prevented. Easy inspection is also required. As for BDBE, unstable failure modes ( fracture, collapse, etc. ) are not allowed. Consideration of failure modes are different between DBE and BDBE as Fig. 2. Stable failure modes (deformation and local boundary failure) can extend to unstable failure ones (collapse and gross boundary failure). Such chain failure sequences should be blocked.

Furthermore, limited failure locations are advantageous for early recovery.

Objectives of risk assessment are different. View point for DBE is confirmation of low risk focusing on probability. Purpose for BDBE is to find relatively weak points with attention to consequent damage.

Table 1: Requirements and performance for structural strength.

	DBE	BDBE
Requirements	Failure Prevention For Safety, Availability and Serviceability	Failure Mitigation For Safety and Resilience
Performance	Any failure modes not occur. Easy inspection	Unstable failure modes ( fracture, collapse, etc. ) not occur. Chain failure sequences not occur. Limited failure locations
Failure modes	Stable failure modes (deformation, fatigue, etc.) and unstable failure modes (fracture collapse, etc.)	Unstable failure modes (fracture collapse, etc., chain failure)
Risk assessment	Confirmation of low risk Focus on probability	Finds of relatively weak points. Focus on consequent damage
Performance evaluation	Conservative evaluation ( For assumed failure modes ) Each component	Best estimation ( For actual failure modes) System failure sequence
Evaluation method	Conservative evaluation* ( For assumed failure modes ) Each component	Best estimation** ( For actual failure modes) System failure sequence
Performance improvement	Risk informed optimization of design, fabrication and maintenance (Graded approach )	Fracture control (Failure mode and failure sequence) Risk informed combination of fracture control with accident management

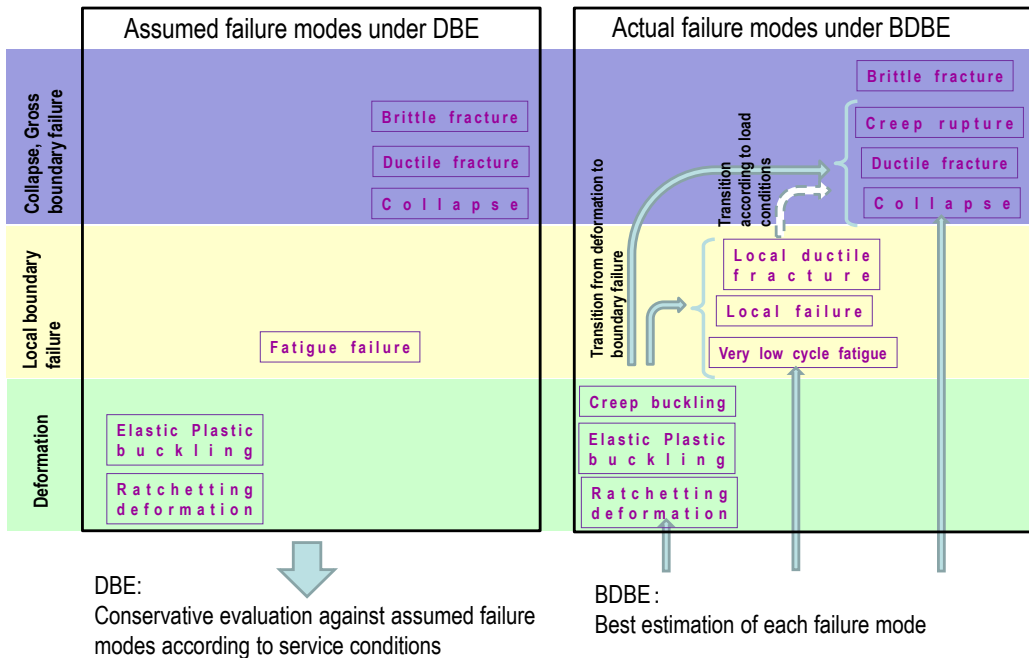


Figure 2. Different consideration of failure modes between DBE and BDBE.

## EVALUATION METHODS FOR BDBE

Structural strength evaluations are different for DBE and BDBE as shown in (?) Table 1. Conservative evaluation methods are suitable for DBE to prevent any failure modes. Design codes for DBE provides conservative allowable limit (rule). Therefore, exceedance of those limits does not mean actual failure.

For BDBE, prediction of actual failure phenomena is necessary to find weak points and determine effective countermeasures. Conservative methods are not suitable to predict actual failure locations and their order. Best estimate methods are necessary for BDBE.

Consideration of failure modes are also different between DBE and BDBE as Fig. 2.

Figure 3 shows failure modes of vessels under high pressure and temperature. The left is ductile fracture, which may occur under small triaxial stress conditions. The right is local failure under large triaxial stress conditions. The latter is not considered in the nuclear structural design codes. For identification of failure modes, authors have developed failure diagrams. Figure 4 is the diagram for vessels under high temperature and pressure, which can identify ductile fracture (creep rupture) and local failure (Sakaguchi et. al., 2018).

Another example is an evaluation of failure modes of piping under seismic loading. Figure 5 shows possible failure modes of piping under seismic loading. For BDBE, ratchet is acceptable and collapse should be prevented.

Figure 6 is the proposed diagram for pipes due to excessive earthquake (Bari et.al.,2017), which can identify ratcheting deformation and collapse.

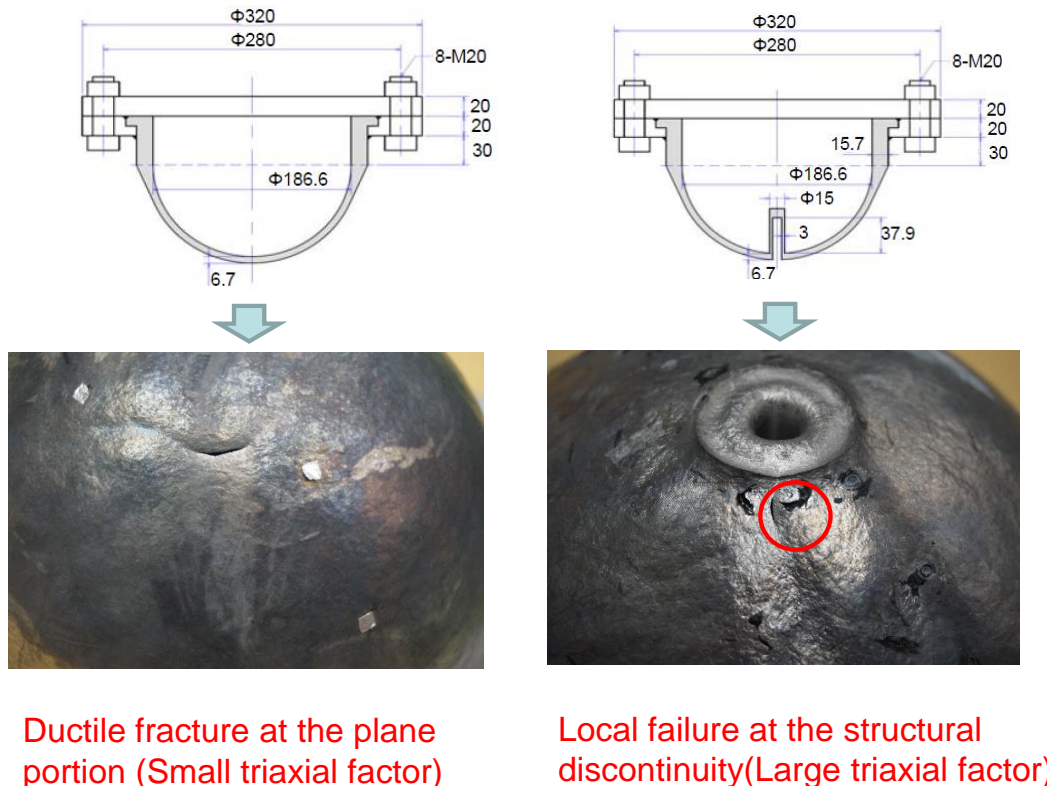


Figure 3. Failure modes of vessels under high pressure and temperature.

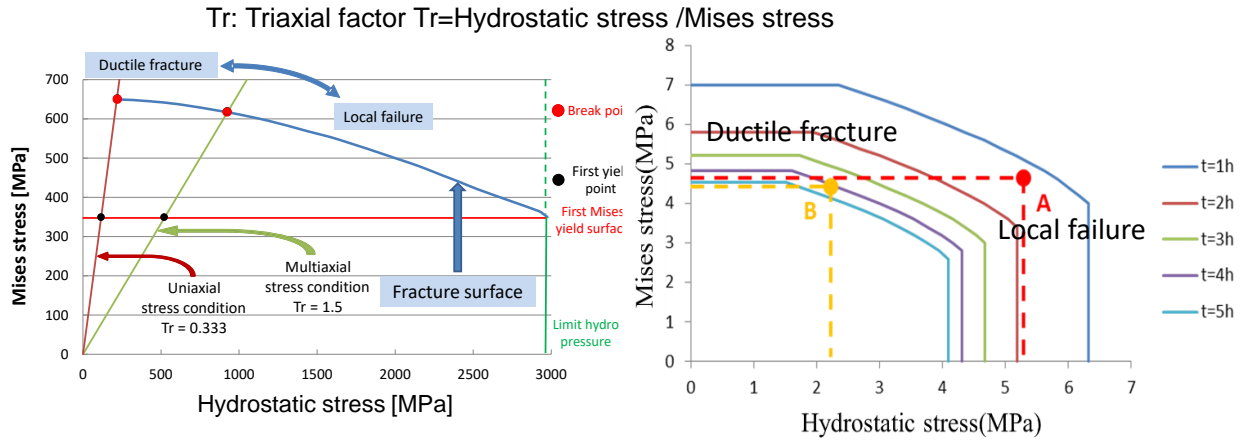


Figure 4. Proposed failure diagram for high pressure and temperature.

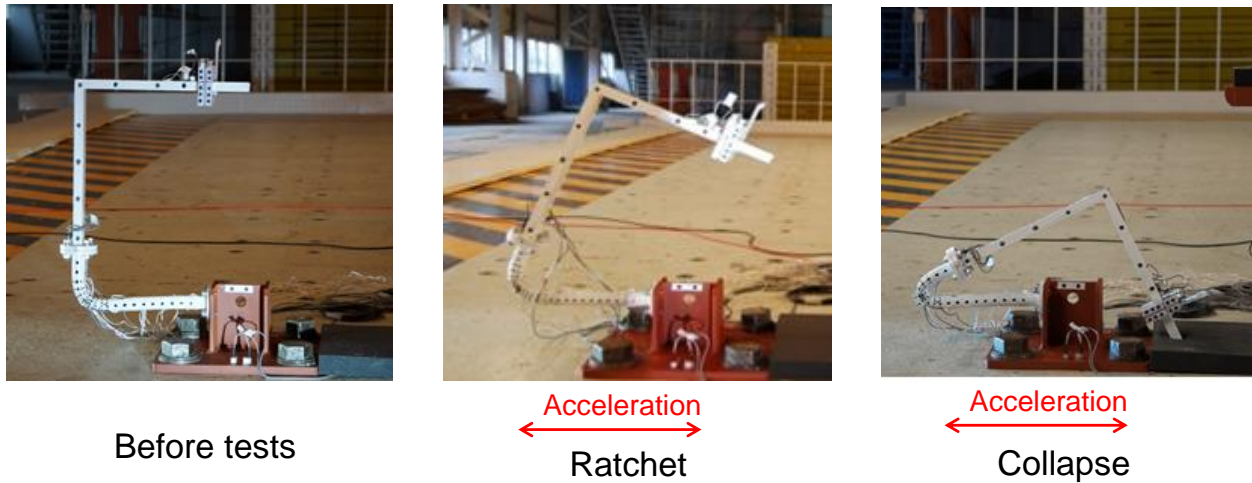


Figure 5. Failure modes of piping under seismic loading.

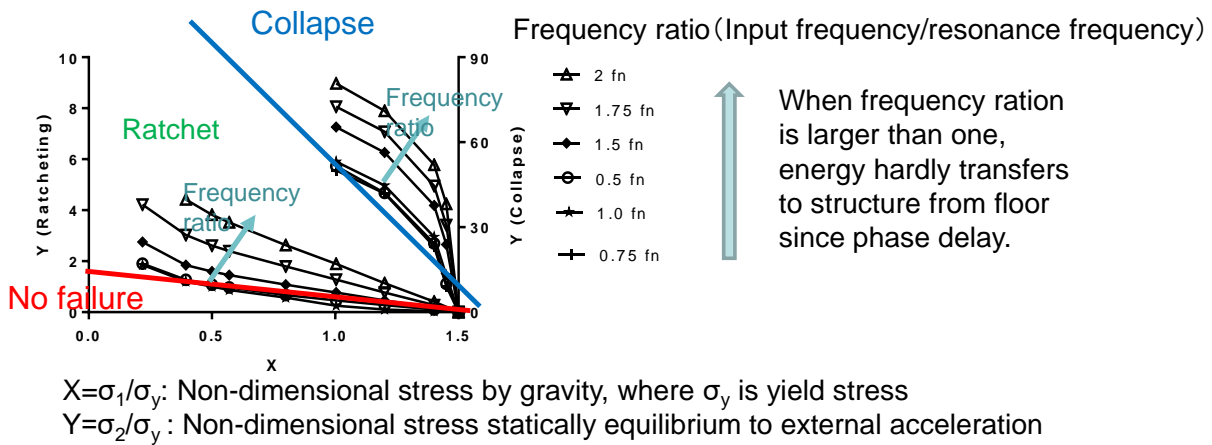


Figure 6. Proposed failure diagram for excessive earthquake.

## MITIGATION OF FAILURE CONSEQUENCE BY FRACTURE CONTROL

This paper proposes performance improvement approach for mitigation of failure and their consequence.

One is the fracture control and another is the risk informed combination of fracture control with accident management (Table 1).

### *Fracture Control*

Authors propose application of fracture control concept for mitigation of accident consequence of nuclear plants as contribution from structure and material fields (Kasahara et al., 2017).

Figure 7 shows an example of fracture control for the cone roof tanks of process plants. Strength of the junction between roof and side wall is controlled weaker than the junction between base plate and sidewall. When over pressurized, junction will break prior to sidewall and protect sidewall by pressure release (Sato, 2013)

Figure 8 shows two example proposals for nuclear plants. In the case of reactor vessels under high temperature and pressure conditions, small cracks from local failure will release internal pressure and can avoid a large scale ductile fracture of general portions. For piping under excessive earthquake, plastic deformation consumes vibration energy and can prevent collapse and break of pipe wall. Strength of pipe supports can be designed lower than pipe itself. Controlled break of support leads to plastic deformation without the break. Thus, large scale and catastrophic failures can be avoided by energy release due to prior small scale failure.

Key issues for fracture control are identification of failure location with their failure modes. When order of failure location and modes can be controlled, fracture control becomes available. Here, absolute strength evaluation for each failure mode is not easy especially for BDBE. However, fracture control requires relative strength evaluation among different failure modes, which is much easier than absolute strength.

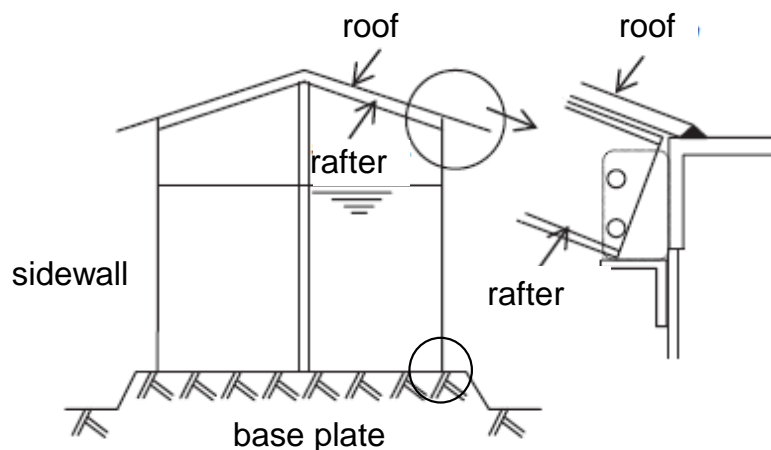


Figure 7. Example of fracture control in process plant.

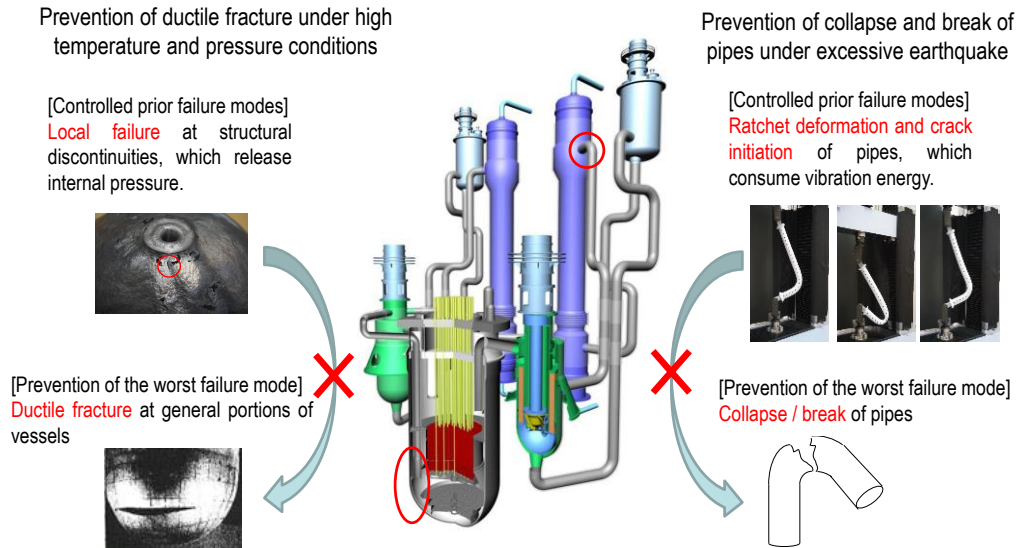


Figure 8. Example of fracture control for next generation reactors.

### ***Fracture control and combination with accident management***

Fracture control limits failure locations. Therefore, it will enable effective accident management.

For example, core damage accident of fast reactor will enforce high pressure and high temperature loads to the reactor vessel. Fracture control approach can limit failure locations within upper portions of the vessel than liquid surface with head access nozzles as in Fig. 8. If vessel failure will occur over the liquid surface, it will release internal pressure without sodium leakage. Therefore, accident management can focus on cooling of decay heat, and will achieve quick recovery.

Effect of fracture control with accident management can be evaluated by PRA. Risk informed approach is available to improve failure mitigation methods.

## **CONCLUSION**

After Fukushima nuclear power plant accident, countermeasures to BDBE were strongly recognized.

However, previous efforts in the structural strength fields focused on design area. There are few activities and are no suitable approaches for BDBE.

For BDBE, prediction of actual failure phenomena is necessary to find weak points and determine effective countermeasures. Conservative methods are not suitable to predict actual failure locations and their order.

This study proposed the failure mitigation approach for BDBE in the structural strength field.

One is the fracture control and another is the risk informed combination of fracture control with accident management.

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