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A REPORT OF LATEST RESEARCH PROGRESS ON THE BEYOND DESIGN BASIS DESIGN CONSIDERATIONS FOR GEN III & IV NUCLEAR POWER PLANT

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ABSTRACT

Beyond design basis (BDB) consideration, as a new design philosophy evolved from lessons-learned in practices of nuclear engineering, is becoming a hot topic in new nuclear power plant design for GEN III & IV plants in recent years. With the improvement of safety and quality requirements, beyond design basis design (BDBD) have become a required engineering aspect from technological and regulatory point of view**.** BDBD actually is a comprehensive description regarding of all potential worse case scenarios which are not considered in the codes' design basis. In short, BDBD comprises of internal (inside containment) events, external natural events and man-made threats etc. Among all these worse case events, strong earthquake is the most power impact to the whole plant with a relatively higher possibility during the design service-life of a plant; the lessons learned from Fukushima accident have proofed it. In the event of a strong earthquake, the plant's structural frames / walls and envelopes will first undertake the shock wave and associated vibrations (which oftentimes are given as the spectra of accelerations in the design); the vibrations then be transferred from structural baselines to other systems and components which are the essential parts of the functional equipments for the whole plant. The purpose of this paper is to summarize the research results and progresses of authors in recent years, which include: (1) The recommendation of an overall framework for beyond design basis (BDB) seismic design; (2) the analysis procedure (modelling, input factors / analysis parameters modification); (3) the application of prevailing industrial codes and incorporation of Elasto-plastic method to BDB seismic design. As conclusion, a comprehensive BDB seismic procedure is recommended in this paper. For design purpose, an Elasto-plastic approach was established with the respect to strength design method employed in current concrete structural design.

THE NECESSITY FOR BDBD CONSIDERED FOR SAFETY-RELATED FACILITIES

The Frequency of Strong Earthquake in Recent Decades

As we all know, nuclear power plant (NPP) design and construction rules in 21st century require the designer not only take design-basis loadings (DBL) into account but also consider some beyond the design-basis loadings (BDBL) which are relatively with high probability of occurrence and potentially could damage the performance and integrity of NPPs. According to the source of loading, BDBL can be largely divided into "internal events" and "external events". Internal events mainly consider the failures of structure-systems-component (SSC), and their subsequent impacts; while external events focus on the environmental phenomenon such as: (1) earthquake (seismic), strong wind (tornado), flooding (include tsunami) (2) climate influences (extremely hot /cold) and (3) adverse human influences – such as terror attack. This paper as the subsequent research report on BDBD topics focuses on BDB Seismic (BDBS) considerations for new NPP design-build. The reason to do so is because compared to other environmental loadings, BDBS has following features: (1) it could happen at a relatively high probability, (2) if happened it can influence / impact very large area, (3) if happened it may resulting in very severe damage. Following is a brief statistics of strong earthquakes which happened in most recent 100 years.

Table 1: The comparison of severity and occurrence time interval of earthquakes happened in early 20th and early 21st century

Earthquake	Country / Region	Time of Occurrence	Magnitude (Richter)	If (?) Tsunami	Note (Century)
Indonesia Strong Earthquake	Indonesia / Sumatra Island	2004.12.26	**9.0**	Y	21st
Wenchuan Earthquake	China / Wenchuan	2008.05.12	8.0	N	21st
Samoa Island Earthquake	American Samoa	2009.09.29	8.0	Y	21st
Tohoku Earthquake	Japan / Fukushima	2011.03.11	**9.0**	Y	21st
Indonesia Strong Earthquake	Indonesia / Sumatra Island	2012.04.11	8.6	N	21st
Kashmir Earthquake	Kashmir	1905.04.04	8.0	N	20th
Valparaiso Earthquake	Chile / Valparaiso	1906.08.17	8.4	N	20th
Dushanbe Earthquake	Tajikistan / Dushanbe	1907.10.21	8.0	N	20th
Ningxia Haiyuan Earthquake	China / Haiyuan	1920.12.16	8.5	N	20th

Based on the records in Table 1, there were four strong earthquakes (measured above M8.0 per Richter scale) happened in early 20th century in 20 years (1900 - 1920). There are 5 strong earthquakes occurred in early 21st century in 10 years (2004 - 2014), among which two earthquakes are measured even above M9.0 per Richter scale.

With comprehensive investigation on earthquake phenomenon and the advancing of design-construction practices, human being already build up advanced codes / standards which are widely applied in commercial and industrial buildings. Fundamentally speaking current codes / standards are based on the principle that the exceeding of design loads and the corresponding failure of structure are all within the probability of about 5 percent. To assure this during design, the codes / standards will define a set of basics called "design-basis" (DB), it is a verified reasonable maximum design inputs (e.g. loadings). It is assumed that if designer follows this principle, the structure theoretically will never exhibit a failure (such as collapse); and this, as we all know, is called **design based on DB loading**.

Based on lesson-learned from Tohoku-Fukushima earthquake and the latest records of strong earthquakes data (see the brief summary in Table 1), it might be concluded that the earthquake occurrence and activity are having an obvious increasing trend. Its reasons are not clearly known, maybe related to the Big Cycle of Seismic Events, or it is related to human being activity which could influence the global environment. As an overall, the occurrence of strong earthquakes, especially some of those beyond the design-basis (BDB) limit are increasingly encountered in early 21st century. Considering the lesson learned from Fukushima Accident and the rethinking topics discussed in author's SMiRT 22 paper, it is necessary to consider BDB seismic design in GEN III plant, and the demand to find an appropriate way to integrate BDB methodology in current engineering design processes are in great need.

The Necessity to Consider BDBD as an Engineering Requirement from GEN III Plant Design Point of View

- The NI layout and the increasing of major equipment size / weight

General Configurations of GEN III nuclear island (NI): In most of the cases NI comprises of areas in which the safety-related or safety-important SSCs are located. Figure 1 shows the configurations of a typical NI layout (marked by bold red line), which is used in AP and CAP plant design.

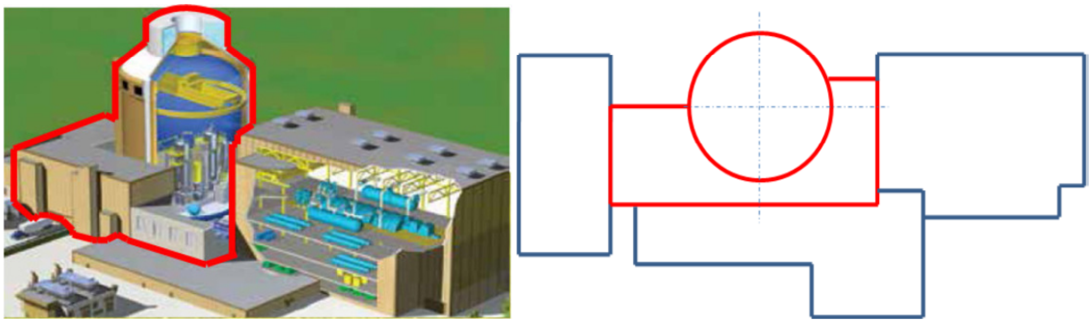

Figure 1: Typical layout in GEN III plant design

The Role of NI Basemat in GEN III Plant Design: Structurally speaking, a common basemat layout for GEN III NI can greatly reduce the analysis efforts required for design. By relying on the advantage of such a design, the majority of safety-related (seismic category I) SSCs are located onto NI basemat, as such they will share same seismic design inputs (SSE) from the bottom of common basemat.

Major Loads Undertaken By Basemat:

Figure 2 on the right shows safety-related building structures which are located within NI area of an AP / CAP plant:

1) Shield Building (SB) - shown as ② in Figure 2
2) Steel Containment Vessel (SCV) – shown as ③ here
3) Containment Internal Structures (CIS-all inside SCV)
4) Auxiliary Buildings (AB) - shown as ① here
5) Main Control Room, Fuel handling area, Radwaste Area etc.

For NI basemat global analysis and design, following loading conditions are considered:

(1) Dead Load (2) Live Load
(3) Lateral Soil Pressure (4) Buoyancy Force
(5) Seismic Load (6) Wind Load
(7) Pressure Load
(8) Thermal Load

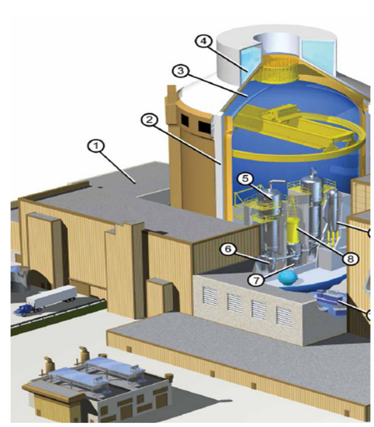

Figure 2: Safety-related Building Structures Located within NI Area

- The complexity of SSC design

Generally speaking, GEN III NI design succeeding GEN II NI design features and improved it to a level which can accommodate an innovative two / three Steam Generator loops and associated equipments, systems and shielding structures. Due to SCV volume change, the structural dimensions of shield building are increased; as a result the NI basemat dimensions will be also increased to achieve a robust foundation design for such new generation of plant.

Figure 3 shows the complex SSCs elevation (EL.60′ to EL. 333′) of NI containment internals; foundation basemat, the major upper structures are also included

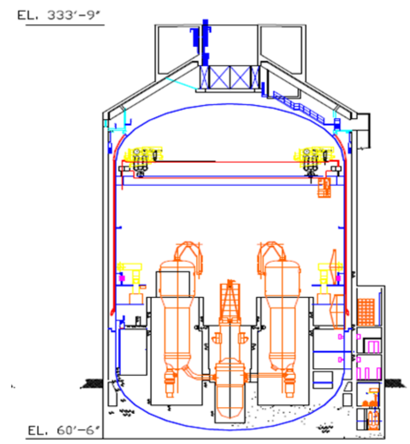

Figure 3: Complex structure – system – component within NI

- The increasing cases of soft soil site conditions

With the increasing of NPPs' number around the world, the preferred good sites (e.g. close to coastal area and underlined by bedrocks) are becoming hard to identify; this especially is the case in China, who has chosen nuclear power as the mainstream clean energy for 21st century. As the result, some inland good locations are selected as the candidate sites for new build in the future. Since compared to coastal areas with shallow bedrocks, the geotechnical conditions of these types of site oftentimes are characterised as soft soil conditions without bedrocks or the bedrocks are located in great depth. For plant engineering design-analysis of such soft soil condition, the designer will have to partly consider the application of / substitution with engineered soils and in the same time model the underlined soil layers together with the foundation in order to perform a so-called soil structure interaction (SSI) analysis to evaluate the amplification effects of earthquake force when seismic waves transferred through the existing soft soils between bedrock and foundation basemat. Because of the sensitivities of soft soil layers, earthquake force could be amplified even greater when considering it is due to a BDBS event. So BDB seismic consideration shall be fully incorporated in BDB design procedures; it is the critical part of BDB design utilized to enhance DB design.

The Requirement from Regulatory Agencies

- The US nuclear authority requirements regarding BDBD after Fukushima accident

US NRC published following requirements and practical guidance based on the investigations and lessons-learned from Fukushima Accident.

(1) NUREG / KM-0008: "NRC Senior Leadership Visit to Japan", 2014
(2) EA-12-049: "Oder Modifying Licensees with Regard to Requirements for Mitigation Strategies for Beyond-Design-Basis External Events"
(3) JLD-ISG-2012-01: "Japan Lessons-Learned Division Interim Staff Guidance" Final Rev.2 2018.04

In the previous Orders / Guidance, NRC has taken significant action to enhance the safety of operating reactors in the United States. These documents by thus far provide clarification to assist nuclear power reactor licensees with the identification of measures needed to comply with requirements to mitigate challenges to key safety functions. As the specific requirements, following mandate tasks have been recommended to satisfy requirements:

(1) Flooding Hazard Re-evaluation
(2) Seismic Hazard Re-evaluation

(3) Mitigation Strategies Assessment

US DOE embarked upon several initiatives to investigate the safety posture of its nuclear facilities after Fukushima accident. As the results DOE issued safety Bulletin 2011-01, conducted two DOE nuclear safety workshops. Further, the Office of Nuclear Safety developed a Protocol for Enhanced Evaluations of Beyond Design Basis Events (BDBE) Supporting Implementation of Operating Experience Report 2013-01. The purpose is to provide a vehicle through which interested parties can keep abreast of the latest status and actions related to DOE's efforts to analysis, prepare for, and mitigate beyond design basis events.

- The NRA (Japan) requirement - Newly proposed regulatory requirements for light-water nuclear power plants

The Japanese regulatory authority, nuclear industry and research entities conducted extensive investigation and research to unveil important causes which lead to Fukushima accident and the lessons-learned from it. The newly formed Nuclear Regulatory Authority (NRA) of Japan has published many investigation / research reports to the public domain which definitely benefit nuclear power industry all across the world. Through almost 9 years investigation, the NRA concluded the root causes of Fukushima accident, summarized the lessons-learned and recommended new requirements which cover the regulatory policy and rule making focuses. Following is the brief summary of the New Regulatory Requirements from NRA in Japan：

Regulatory policy / rule:
(1) Place emphasis on defence-in-depth concept
(2) Assess and enhance protective measures against extreme natural hazards
(3) Take measures against severe accidents and terrorism
(4) Eliminate common cause failure
(5) Make much account of “diversity”, shifting from “redundancy focused”
Standard / requirement:
(1) More strict standards on tsunami
(2) Clarification of requirements for fault displacement
(3) More precise methods to define Design Basis Ground Motion (DBGM)
(4) Assessment & monitoring of volcanic activity

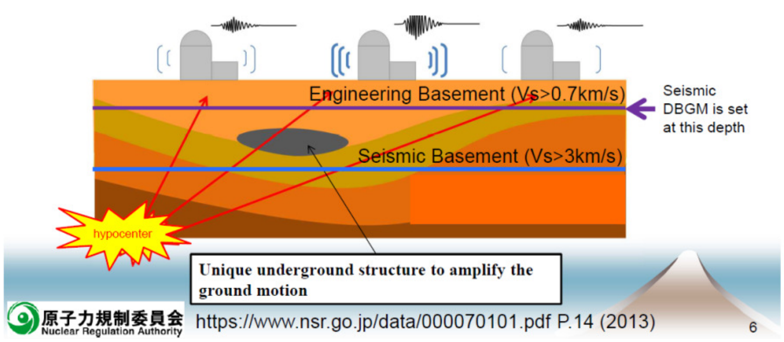

Figure 4: Design Basis Ground Motion (DBGM)

THE RECOMMENDATION OF AN OVERALL FRAMEWORK FOR BEYOND DESIGN BASIS SEISMIC DESIGN – “THE ASPECTS OF APPROACH”

With the background and consideration discussed in previous section, the authors recommended an overall framework for BDBS design based on latest research and the previous related works which are already published on international conferences.

A Brief Summary of Author's Previous Works

- The works between 2009 to 2013

This paper is a preliminary research summary on BDBD, primarily focused on the BDB phenomenon aspects of seismic events and the related tsunami impact on nuclear power plants. The summary is based on an investigation of the beyond design basis seismic event and tsunami loadings and their impact to safety-related nuclear shielding structures of the NPP, and how failure of such structures impact the safety features of the plant and the safety functions of the systems and equipment. In addition, this paper covers ways to reduce the impact and mitigate the consequences of a certain accident by pre-incorporated measures in the structural design.

This paper pointed out that for a NPP, the well-designed reactor system and equipment with high reliability do not certainly ensure that the whole NPP is absolutely safe. In fact, the plant shielding structure's design (the layout, design analysis, installation and construction) and its safety-related functions all play their parts to determine the ultimate safety features of the NPP. The Fukushima Daiichi accident revealed this hidden root cause embedded in old codes and approaches, and caused us to consider new standards and methods which will include the BDPD, and re-define the design safety roles of structural and civil related scopes to achieve a comprehensive higher standard for NPPs under the beyond design-basis loading and accident condition.
As the results, the author gives recommendations in the conclusions that can be outlined as following:

(1) Beyond Design-Basis Phenomenon (BDP) Design for NPP can be considered by a means of up-scaling the design basis loading conditions to increase the existing design margins defined for design basis loading /or design basis accident condition. In this way, the plant SSCs obtained an extra capability to resist BDP loadings such as BDBS loadings.
(2) Before the fulfilment of the full transition of current code from deterministic method to **probabilistic** approach, the most economic way to perform a BDBS design is to indirectly apply the PRA and PSHA method in the determination of beyond design basis input loadings conditions. In another word: first determine the design-basis loading condition or design accident loading condition by the PRA or PHA method, then scale these results based on the target annual exceedance frequency of acceptable performance to get beyond BDB inputs.
(3) A realistic BDBS approach: a realistic BDBS approach means a comprehensive and fully integrated probabilistic methodology which is integrated for BDB design.

- The works between 2014 to 2016

Even though in the past 30 years, Beyond Design-Basis Phenomenon Design for nuclear power plant (NPP) has been considering as one of the design commitment for the safety and function goals, often time a compromise inevitably takes the place when conduct the detail engineering design. There is several reasons lead to this situation: (1) the lacking of thorough investigation and research on this subject, (2) the need for clarity and recommendations from industrial code and standard practice, (3) the need for clearer and specific regulation and regulatory requirements, (4) the consideration of economy.

By understanding the above situations, the works in this paper are contributed to investigate the determination of Beyond Design Basis Seismic (BDBS) design for new NPP in current timeframe. Due to the complexity of this new emerging subject, this paper, as the carrier of detailed results, gave further discussion on BDB engineering considerations which include the necessity for incorporating BDBS in design phase, how to consider BDBS in design phase and recommended frameworks for BDBS determination and its approach / procedures.

Overall Framework for Beyond Design Basis (BDB) Seismic Design

- The choosing of PSHA

BDB earthquake, because of its highly improbable nature of occurrence, the fully adopting of probabilistic methodology is the best (economic) way to address all types of issues for beyond design basis considerations. But due to the limitations of probabilistic theory application in current codes and standards, it is recommended to go through a transition from deterministic method to a probabilistic approach. For practical purposes this transition could be in a stepped way. For instance, it can start from a safety margin based assessment, and then may choose to go through a partially / semi-probabilistic method; the ultimate goal of this transition is the integration of full probabilistic method to new NPP's engineering design. Following table showed the processes of such a transition, and reveals the relationship.

Table 2: BDBS design level

Category (Origin of Design-basis)	Design Level			
	Deterministic	Partial probabilistic	Semi-probabilistic	Full Probabilistic
Current code/standard	Y	N	N	N
Industry Provision/Requirement	Y	Y	Y	N
New method	N/A	Y	Y	Y

The BDBS "design category" is classified according to the origin of design-basis, it can be prevailing codes / standards, well established industrial provisions / requirements by regulatory authority, and new method recommended by industrial experts based on academic research and technical investigation. The BDBS "design level" is divided based on what technique (approach) is used to determine the beyond design basis event loading conditions. Deterministic approach is a dominated method in current codes and standards. Partially probabilistic and semi-probabilistic are both quasi-probability method to deal with seismic margin evaluation, which somehow can give a reasonable determination on BDBS loading conditions, especially for earthquake loading cases. Full probabilistic is the method recommended by authors, which basically is the application and integration of PHA or PSHA method in BDBS loading determination and analysis / design processes.

- The integration of PSHA method to BDBS

It is well known now that for a NPP, the well-designed reactors; systems and equipment with high reliability do not certainly ensure that the whole NPP is absolutely safe. In fact, the plant shielding structure's design and its safety-related functions all play their parts to determine the ultimate safety features of the NPP. Fukushima Daiichi accident revealed this hidden root cause embedded in old codes and approaches, and caused us to consider new standards and methods which will include the BDBS, re-define the design safety roles of structural and civil related scopes to achieve a comprehensive higher standard for NPPs under the beyond design-basis loading conditions.

1) "BDBS Identification": For civil-structural, beyond design basis events considerations are mainly those natural / environmental loadings such as earthquake, tornado, tsunami etc. PHA and PSHA are utilized to identify the most severe event such as **control earthquake** which is considered as BDB here.
2) "BDBS design input determination": Probabilistic hazard analysis shall be used for determining DBD loadings which were identified previously, such as seismic loads etc.
3) "Load combinations": Generally speaking external BDB event occurs in a very infrequent way. The possibility of occurrence of two BDB events at the same time is extremely infrequent. But they possibly could occur in a short elapse of time next to each other (such as Fukushima Earthquake and

subsequent Tsunami). So **critical load combination** for BDB seismic design should consider one BDB seismic loading combined with normal design loads at a time. But design engineer need to pay attention to those normal design loads since their actual magnitudes might be increased in the case of BDB (i.e. the BDBS load possibly could induce additional normal design loads).

4) BDBS design modeling requirements is discussed in the next Section
5) BDBS design analysis requirements is discussed in the next Section

- <u>The recommended framework</u>

Following flowcharts provide recommended frameworks for new NPP engineering design. It can serve as an effective approach before any BDBS code requirements are published.

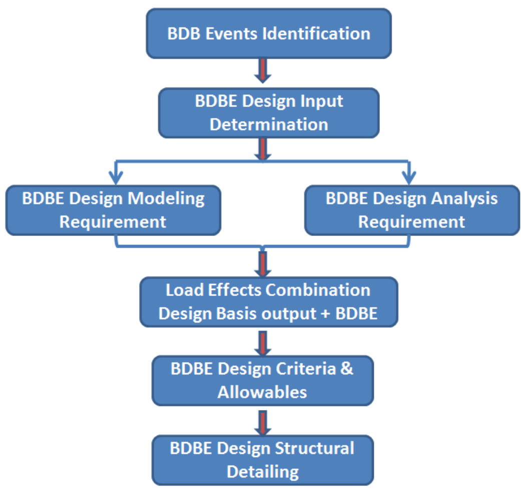

Figure 5: The basic design flowchart of BDBE for new NPPs

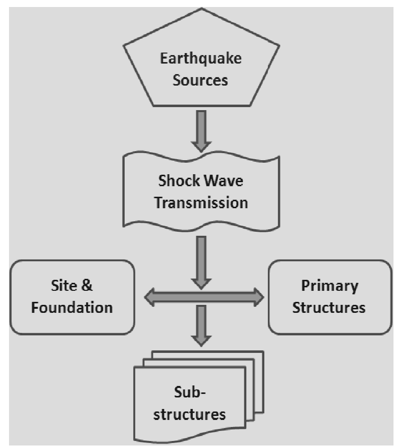

Figure 6: Seismic design logic flow-chart

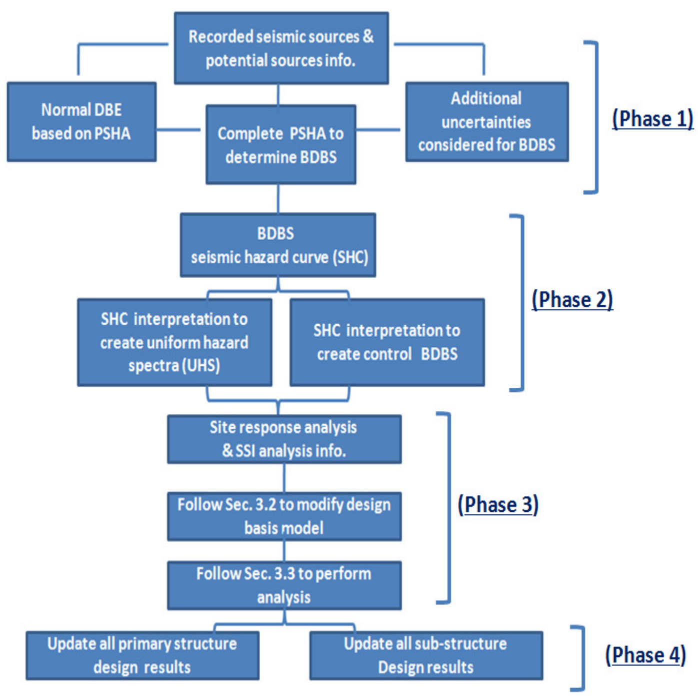

Figure 7: Integrated complete probabilistic framework for BDBS design

THE ANALYSIS PROCEDURE FOR BDBS DESIGN – "THE ASPECTS OF MODELLING & ENGINEERING ANALYSIS"

The Establishment of Procedural Baselines

Fundamentally speaking, BDBE is the same as that of design basis design; since beyond design basis phenomenon design actually is an engineer-defined design loading limit to cope with engineering design challenges and economic issues. It keeps changing with the advancing of (1) Material technology, (2) Engineering analysis and design philosophy and (3) Construction techniques. So a realistic BDBS approach from the authors' point of view is a method in which all previously aspects of (1), (2) and (3) are coming together under the comprehensive and fully integrated probabilistic principles.

Based on authors' research and investigation, BDBS design-analysis actually is not only a matter of the determination of BDB seismic loading cases itself, it further demands the considerations on the model modification (e.g. cracking condition, adjustment of stiffness, strain-stress condition etc.) to match the energy absorbing condition of the structure which subjecting to BDB seismic dynamic loadings.

In another word, BDB event is the same as that of the design basis; since beyond design basis phenomenon design actually is an engineer-defined design loading limit to cope with engineering design challenges and economic issues at a certain timeframe of technological development. It keeps improving with the advancing of:

(1) Material technology
(2) Engineering analysis and design philosophy
(3) Construction techniques etc.

So a realistic BDB seismic approach, from the authors' point of view, is a method in which all previously stated aspects (1), (2) and (3) are coming together under the comprehensive and fully integrated probabilistic principles.

The Structural Modelling for BDBS

BDBS analysis modeling still follow the basic principles defined in national codes, industry standards etc. But since the magnitude of beyond design basis loading condition will definitely push the structure into more plastic stage (higher ductility level), the model built for original design-basis seismic analysis need to be modified to incorporate new criteria and parameters to reflect the true conditions for BDBS design. Following recommendations from authors can serve as general requirements for BDB modeling for seismic:

(1) Perform summaries of design basis earthquake (DBE) modeling information & analysis information.
(2) Re-establishment of BDB seismic model considering following aspects:

- Considering modification on BDBS ground motion response spectrum (GMRS)
- Determination of appropriate load combinations to include specified beyond design basis seismic loads
- Modification of material strength as necessary
- Modifications of capacity equations considering the conservatism of code equations
- For ductile failure modes, consider ductility benefits and go to higher ductility level than what used for design-basis seismic analysis.
- Re-define local yielding conditions by the means of referencing the ductility level used for the design-basis analysis

(3) The superstructure model and foundation model modification considering SSI analysis.

The Consideration of Design-Analysis Requirements

By considering above modeling requirements for BDBS, the analysis requirements can be summarized as follows:

(1) Structural capacity should consider ACI ultimate strength, AISC maximum strength, or ASME equations corresponding to service level D whichever is applicable, maximum strength resulting from reliable test data is also recommended
(2) For structural inelastic energy absorption effects, a higher ductility level can be considered because of the tolerance of development of greater local yielding areas.
(3) Modal damping can consider higher values corresponding stress level 2 and higher for BDBS analysis
(4) Need to capture response mode shapes and combine them in an appropriate way to facilitate BDBS analysis.
(5) Static nonlinear or dynamic nonlinear analysis should be performed to investigate ductility level and energy absorption characteristic.
(6) Consideration of additional normal loadings due to the occurrence of beyond design basis loadings (additional normal loadings induced by BDBS)
(7) Suggest using both frequency shifting and peak broadening to generate in-structure spectra for SSCs design and qualifications.

The Validation and Verification of BDBS Design-Analysis Results

One significant thing which shall be pointed out is that even for BDBS design, existing design-basis earthquake design results still should be taken as the reference-line to perform comparison between BDB seismic and DB seismic. Reasonable crosschecking and updates or modification to DB design and BDB design shall be conducted to validate / ensure BDBS analysis results are meaningful, reliable and with economic considerations

THE INCORPORATION OF ELASTO-PLASTIC METHOD FOR BDBS DESIGN – "THE ASPECTS OF ENGINEERING DESIGN"

Beyond Design Basis (BDB) Design and Design Basis (DB) Design – Their Compliance & Difference in Engineering Nature

Just as stated previously, BDB design can be considered the same as that of DB design; since BDB phenomenon design actually is an engineer-defined design loading limit to cope with engineering design challenges and economic issues. It is well known that current key codes / standards design philosophy for NPP design are largely classified into elastic design (working stress - linear method) and strength design (ultimate stress - nonlinear / plastic method). As one of the main stream design codes for NPP, the ASME code is based on working stress method for all of its design guidance; meanwhile current ACI-349 code for NPP is based on strength design methodology. To bridge these two codes, ACI-359 (ASME III DIV.2 code) was established and set forth design criteria / standards for nuclear concrete structures which are within or related to nuclear safety boundary (pressure boundary). So in reality, there is no very clear condition (interface) that differentiates the Beyond Design Basis (BDB) from the conventional Design Basis (DB). From engineering practice point of view, a transitional phase (stage) is always applicable to bridge DB condition to BDB circumstances. BDB design even though is different from DB design, it still complies with the theorem well established in DB design principle which is the dominated main stream codes in all current engineering practices.

The Basic Principles of Elasto-Plastic Method

- An example comparison of abnormal working condition (severe) to BDB condition

<u>Definition:</u>

(1) "Abnormal working condition" (severe) generally is the worst case of design basis condition. In almost all the cases it is related to high-energy pipe break and associated missile impact / impingement. Abnormal working conditions are specifically applicable for nuclear island internal SSCs' design. Since abnormal working condition is categorized as a transitional condition here, it still

can be treated as of within the design basis range, the design shall fully ensure the integrity of internal SSCs in order to maintain the safety function required for reactor operation.

(2) "BDB conditions" here refer to the external events which may associate with the very infrequent natural phenomenon, such as Earthquake, tornado / tornado missile and tsunami; or human adverse effect such as terror attack. Current codes / standards do not provide the provisions for such beyond design basis cases. So the early stage of BDB loading oftentimes was treated as "severe abnormal working condition", and thus falls into the border of "design basis" case. Based on such a background, industrial design practices treat such design scenario by the way of "Design Extension" , which in many ways are serving as post-design verifications using the same model as for design basis cases; hence not truly (completely) reflect the situation and nature of safety-related SSCs subjected to BDB loading conditions.

- Design method

For safety-related PCCV and shield building design under abnormal working condition, it primarily follows post-strength method or Elasto-plastic method with the consideration of cracked sections in some critical locations and yielding of steel. Shield building designed with SC-Wall under Beyond Design Basis (BDB) Conditions (BDB-related loads) mainly follow Elasto-plastic or plastic method with the consideration of cracked sections in all critical locations and the yielding of steel-plate. The SC wall residual strengths investigation and check are required.

- Design criteria

Abnormal working condition design assuming the structure behaves in a state of Elasto-plastic condition, globally speaking only small areas of the structure are in yielding state due to the impact load effects from internals. The total yield strain or deformation shall be limited within the code limits.

BDB design assuming the structure behaves in a state of Elasto-plastic or plastic conditions, globally speaking large areas of the structure are in yielding state. To control the degree of yielding, buckling and deformation, the BDB load effects shall be carefully analyzed and limited in a range that as an overall will not jeopardize the safety function required for PCCV and shield building.

Example Case Study – "general aspects of shield building SC-Wall BDB design considerations"

- The satisfaction of shield building structural integrity

Based on rigorous strain-stress analysis: after ultimate working condition (strength design), further increasing of load will bring structure entering a stage of plastic deformation in order to absorb strain energy. With the tremendous development of plastic deformation areas, eventually the strength of structure start to decrease (this is the critical turning point) and the signs of failure appear in many locations where plastic deformation developed in higher degree, the detailed strain-stress developing and the relationship is shown in **Figure 8**. Beyond design basis design is established to treat above post-design-basis case: that is to say, beyond design basis design is set up to assure the structure / structural component, under the designated BDB loads, shall behave with adequate residual strength so that structure integrity remains credible; and the functions of safety-related SSCs are effectively protected. Shield Building SC-Wall design under BDB conditions (BDB-related loads) primarily follow elasto-plastic or plastic method with the consideration of cracked sections in all critical locations and yielding of face plate. The SC wall residual strengths investigation and check are required.

- The fulfilment of serviceability (functionality) for the passive safety feature of NPP

To satisfy above BDB design criteria the following aspects shall be carefully considered during the establishment of BDB procedure to assure the passive safety features for AP & CAP NPPs:

(1) BDB loadings are determined from probabilistic hazard analysis (PHA) or deterministic hazard analysis (DHA); as for seismic loading it is determined from PSHA or DSHA. Standard Design should follow a designated BDB level to satisfy a large area considered. BDB loadings for Site

Specific Design follow PSHA or DSHA performed for an individual site, its BDB level is lower than those values determined for standard design previously (standard design values serve as the envelope for all BDB cases throughout the regions).

(2) Under the BDB loading conditions, SC structural component sections are assumed in general elastic-plastic stage, where concrete due to the confinement of face plates can develop some elastic-plastic deformation, mean while the face plates primarily develops plastic deformation due to reduction of composite action and the relative slips between these two elements (some section forces are re-distributed from concrete to faceplate because of the slips occurred).

(3) The ultimate design approach still assuming the section strain is linear; the section stress due to its nonlinear distribution is taken as an equivalent rectangular block for design purpose.

(4) SC-Wall BDB condition assuming nonlinear sectional strain and stress states. The BDB loads determination and section design validation are intended to limit the SC wall and its sections in a stage of elastic-plastic behavior, which on the load deformation curve is in a stage between face plate yielding and start of internal concrete crushing. Through such a two-ends (BDB loads and sections validation) considerations, the SC-Wall BDB design is proven to be able to withstand BDB loads under an elastic-plastic behavior, while no large area permanent plastic deformation and damages occurred in the section. **Figure 9** and **Figure 10** showed the schemes of above phenomenon.

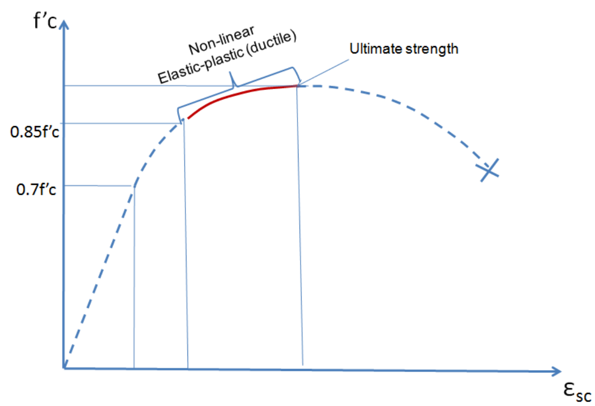

Figure 8: SC wall concrete strain-stress relationships

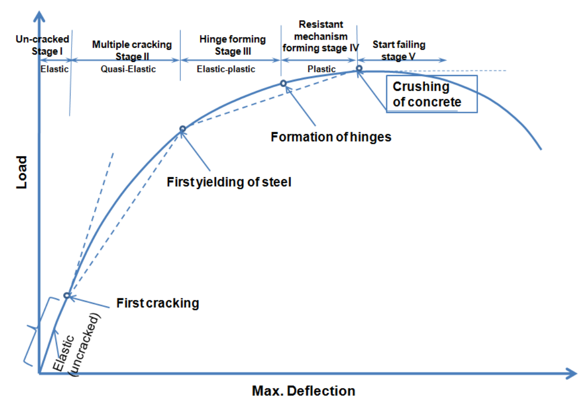

Figure 9: SC wall concrete strain-stress relationships

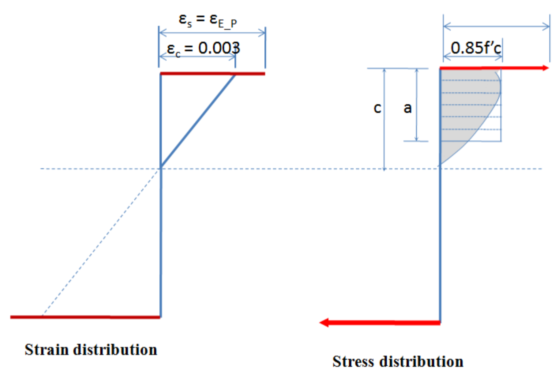

Figure 10: SC wall concrete strain-stress relationships

CONCLUSIONS

By summarizing the investigations and discussions in this paper, we can arrive at following conclusions:

(1) From the trend that nuclear power will be utilized in many countries and the lessons learned from previous severe accidents, it is necessary to establish code / standard and guideline to cope with

beyond design basis design for considering external events such as **earthquake**, tsunami and tornado etc.

(2) Beyond design basis events design are fundamentally different from both “accident condition design-mitigation” and “beyond design basis condition evaluation”. The methodology and approach should come from the principle rules of design.

(3) Beyond design basis event design not only deal with the determination of beyond design basis loading conditions, but also apply the beyond design basis concepts throughout the analysis - design - construction processes to ensure the beyond design basis designs are carried out in an effective and efficient way.

(4) Beyond design basis loading conditions determination still play a critical part in design. Compared to deterministic method, probabilistic method can provide more reasonable result for using as design analysis input.

(5) Beyond design basis earthquake due to its severity and potential damages to NPPs is critical for beyond design basis external event design. The application of probabilistic method such as improved SPRA especially PSHA are recommended. This paper provides brief framework on how to integrate PSHA into a comprehensive beyond design basis seismic design procedures.

(6) Interpreted code “design basis” (DB), and “beyond design basis” (BDB) in a new way in this paper (Section “Their Compliance & Difference in Engineering Nature”), so there is no contradiction and conflict between these two design concepts.

(7) As an example study case, investigated the section behaviors of SC wall subjected to above BDB loadings; recommended criteria suitable for section design and evaluations under such a loading condition.

NOMENCLATURE / ABBREVIATIONS

AP1000	Advanced Passive 1000 (Reactor)
BDBE	Beyond Design Basis Events (Earthquakes)
BDBS	Beyond Design Basis Seismic
CAP:	Chinese Advanced Passive (Reactor)
DBE	Design Basis Earthquake
GEN III & VI	Generation III and VI Nuclear Power Plant
GMRS	Ground Motion Response Spectra
NI:	Nuclear Island
NPP	Nuclear Power Plant
PHA	Probabilistic Hazard Assessment
PRA	Probabilistic Risk Assessment
PSHA	Probabilistic Seismic Hazard Analysis
SFA	Seismic Fragility Analysis
SHA	Seismic Hazard Analysis
SMA	Seismic Margin Analysis
SME	Seismic Margin Earthquake
SPRA	Seismic Probability Risk Analysis
SSC	System-Structure-Component
UHS	Uniform Hazard Spectrum

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