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Introduction of Integrity Evaluation Criteria Developing during and after fire for Nuclear Power Plant Buildings

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1. Introduction

This paper shows the introduction of developing roadmap for structural fire evaluation criteria during and after fire on nuclear power plant buildings. It requires more realistic and engineering based approach method than old fashioned prescriptive one widely used in current fire related code after 911 events. [1~4]

Fig. 1. Fire after 911 event (Refer to Google website)

The first project for nuclear power plant built in Korea to taking account the engineering based approach was started on October 2015 including the whole process such as fire hazard analysis, standard fire modeling, cable tray fire with multi spurious operation, structural fire integrity evaluation, and large area fire induced air craft crash. This paper covers the brief developing scheme and roadmap focusing on structural fire evaluation criteria.

2. Research Developing Divisions

In order to meet the global research trends and needs of nuclear regulatory requirements on nuclear power plant fire, the five research developing areas were set up shown in Figure 1.

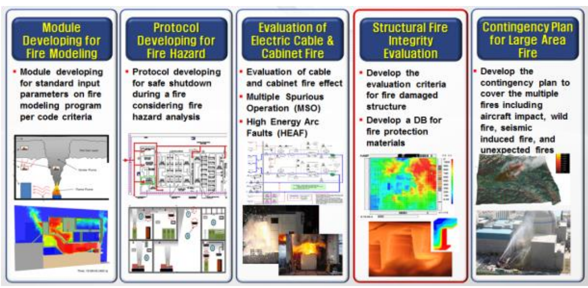

Fig. 2. Directories of Fire Research Project funded by government

2.1 Module Developing of Fire Standard Modeling

There are some specific fire modeling software certified by U.S. NRC (Nuclear Regulatory Committee) but the fire analysis out using certified software were widely fluctuated because of variety input parameters. It is no standard code, guidance or recommendation to input the parameters led to different output. It is required to set up the standard guide considering the relevant affecting parameters based on code criteria.

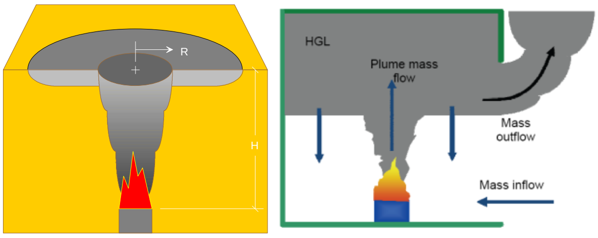

Fig. 3. Schematic of fire modeling

2.2 Developing of Fire Hazard Analysis Protocol

In order to safe shutdown an operating nuclear power plant during an unexpected fire event, it is important to set up the measures per the highest possible fire scenario based on a fire hazard analysis result. The severest fire event tree on nuclear power plant is required to find out using a fire hazard analysis. The protocol developing for fire hard will carry out using all possible fire scenarios in safety related structures, systems and components on nuclear power plant. A verified evacuation plan along with secure route during fire is the one of goal this research. A secure route needs to verify using a fire hazard simulation analysis and experimental testing. A fire hazard analysis method will conduct in this project for operating and construction nuclear power plant.

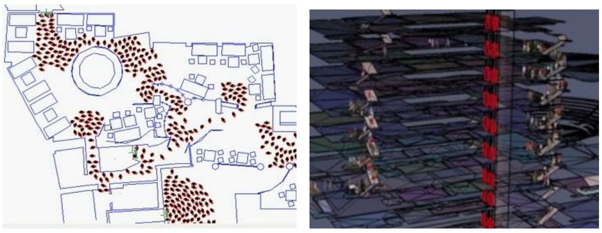

Fig. 4. Typical evacuation simulation model in a commercial building during a fire

2.3 Developing of Electrical Cable and Cabinet Fire Modeling

The cable integrity evaluation for single spurious operation (SSO) and multiple spurious operations (MSO) followed by cabinet fire or high energy arc faults (HEAF) fire has been consistently requested from NRC since 2009 based on the performance to prove the function of cable after fire. There is no attempt to prove those requirements up to now because of non-existing performance based test results. The first trial was started to conduct those SSO and MSO effect of cable after fire on nuclear power plant.

Fig. 5. Cabinet fire due to high energy arc faults (HEAF)

2.4 Developing of Structural Fire Integrity Evaluation Criteria

The remained structural integrity after fire is one of the spot key issues in engineering field. The trial to figure out those remained value was widely started using performance based approach technologies since 911 events up to now. Figure 6 shows the example of experimental testing the composite structure surrounded fire loads. The behavior of structure attacked by fire loads is dramatically different with room temperature one. A fire loads include a heating and cooling process which induced the hysterical loads with large deformation due to creep and relaxation phenomena of material. The behavior of steel and concrete at elevated temperature has totally different because of different thermal properties at elevated temperature. One of the typical material behaviors is spalling effect on concrete material while a structural steel has creep and relaxation phenomena. This is why the performance based research is required

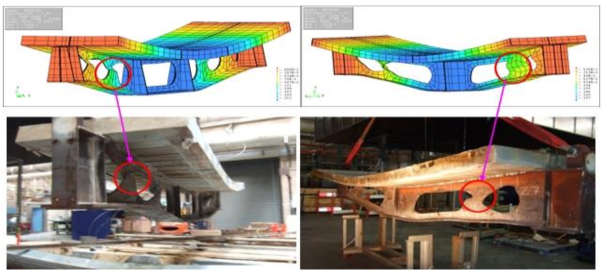

Fig. 6. Deformed composite beam after elevated temperature test compared structural analysis results

2.5 Developing of Contingency Plan for Large Area Fire including Aircraft Crash Fire

The unexpected fire risk on nuclear power plant induced from wildfire, aircraft crash fire and human error fire etc. was severely increased and happened consequently following the asking from regulatory body with heavy and unresolvable questions. Recently, the wildfire surrounded the nuclear power plant had been increased the natural risk. Furthermore, the insistent man-made fire such as terrorist attack, aircraft crash fire or human being error fire is one of the major concerning issues in nuclear regulatory requirements.

The research goal of this large area fire subject is to set the contingency plan as a first step of long journey.

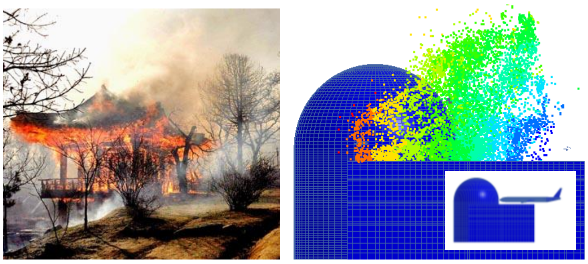

Fig. 7. Wild fire of temple and aircraft crash simulation

With respect to commit the global research trends and nuclear regulatory requirements including domestic and international agencies, the combined fire related research project on nuclear power plant funded by Korea governments was started on October 1st 2015 as four year period.

3. Detail Research Areas for setting the Evaluation Criteria checking Structural Fire Integrity

To develop the evaluation criteria considering structural fire integrity after fire, it requires a full chain of structural fire engineering process including structural fire analysis during and after fire as well as buildup the fire database for construction material used in nuclear power plant buildings. Figure 8 shows the detail research fields to carry out for setting the evaluation criteria of structural fire integrity.

Fig. 8. Detail research areas for setting up the structural fire integrity evaluation criteria

3.1 Evaluation of Structural Behavior during Fire

To estimate the real structural behavior during fire is the essence of structural fire integrity. The performance based resistant capacity is required to prove the structural integrity during fire not only regulatory side but also industrial field since 911 events. Prior to experimental testing, it is a beneficial and convenient way to predict the structural behavior performing a structural fire analysis at elevated temperature. Throughout the fire testing and analyzing on individual structural members with or without fire protection materials, it is possible to utilize them for developing the evaluation system and guide during fire events.

The real scale size fire testing installed all equipment and components for highly potential fire area provided by fire hazard analysis team is going to perform at the end of this project period. These results will be embedded in a guide or criteria for structural fire integrity evaluation. Figure 9 shows the performance testing on structural members such as composite beam, concrete column and wall.

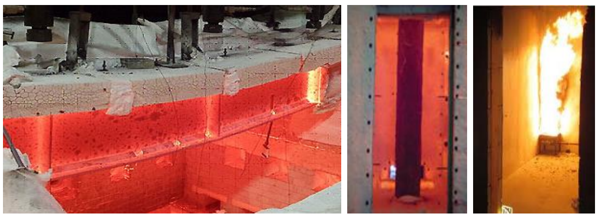

Fig. 9. Fire testing on structural elements(beam, column, wall)

3.2 Developing of Structural Safety Index after Fire

It is essential to prove the structural integrity on nuclear power plant buildings not only after severe fire but also minor fire for the further using. Unfortunately, there are no many studies or researches in a commercial field because of easily rebuild it again while it is hard to banish or rebuild a building on nuclear side for safety related structures. A damaged specimen after cooling is going to investigate the structural integrity using all destructive tests and non-destructive examination methods including. The developing goal is to ensure the remained structural integrity using a residual strength verified by DT or NDT methods.

Figure 10 shows the typical example of non-destructive test using infrared light scanning tools.

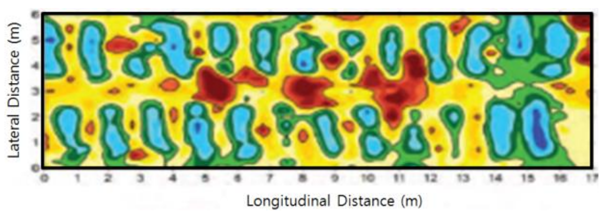

Fig. 10. Infrared light image reflecting damaged concrete

3.3 Buildup Database for Structural Fire Protection

Without mechanical properties of construction materials at elevated temperature, the structural analysis results were not able to estimate the real behavior of structural. These vast works as time consuming job need a huge effort to build the database for using in structural analysis and evaluation works. The accumulated database has strong power to estimate the behavior of structure and to use the protection material. Most countries had their own database for construction material including varies fire protection materials and fire resistant paintings while updating periodically without sharing except for commercial materials.

It is difficult to obtain the database for construction materials in nuclear field at elevated temperature due to the security reason or unopened reason which requiring self-studying and researching. The variety database on construction materials for nuclear power plant building will perform to build up including a commercial product.

3.4 Developing of Structural Fire Integrity

The final stage of this research is to write up the evaluation criteria of damaged structure due to fire. The guide and criteria will useful to estimate the structural integrity after fire on nuclear power plant building. The appropriate damage index based on the residual strength as well as structural integrity index after fire is going to set for the last research year throughout the performance based research.

4. Fire Regulation and Code Updating

The fire code for structures was focused on to perform the prescriptive methods not an engineering based approach. However, the current movement on fire related codes such as NFPA, IBC, ASTM, etc. is gradually oriented to update using a performance based results since 911 events per the global code trend.

This research results want to share with the fire related code committee whom are intentionally collaborated as a research project consultant. It is meaningful to cite the fire test results or database produced by this research project.

5. Construction Material Behavior at Elevated Temperature

5.1 Mechanical Properties at Elevated Temperature

The mechanical properties of construction materials at elevated temperature are dramatically different than room temperature for both concrete and structural steel including composite structures. In general, the mechanical properties of construction material around 500℃ had completely changed their characteristics

The pattern of concrete structure in stress-strain curves shown in Figure 11 has similar from 20℃ to 400℃ while the curves above 500℃ has shift to reduce the strength increasing strain. The strength is dramatically reduced from 500℃ up to 800℃ showing spalling effect which is concrete surface explosion due to boiled water inside of concrete surface [4-6].

The other famous construction material is structural steel which is produced by steel maker with consistent certified quality control program. However, the mechanical properties at elevated temperature are totally different than room temperature. A typical steel phenomenon at elevated temperature is creep and relaxation shown in Figure 12.

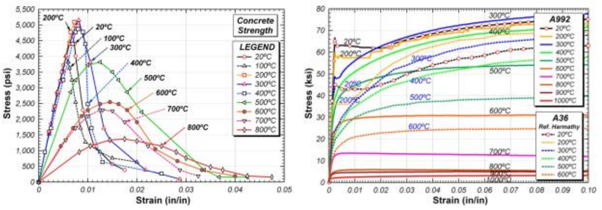

Fig. 11. Stress-strain curves at elevated temperatures of concrete material [5~6] and structural steel [8].

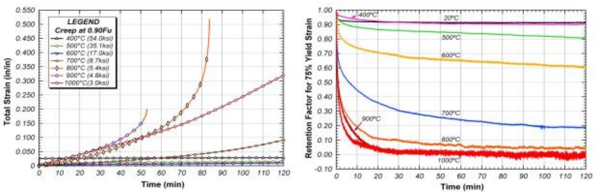

Fig. 12. Creep and relaxation curves of structural steel at elevated temperature [7~8]

5.2 Structural Behavior during Fire

The spalling effect is the crucial phenomenon in concrete around 500~600℃ shown in Figure 13 with schematic diagram and revealed surface after two fire.

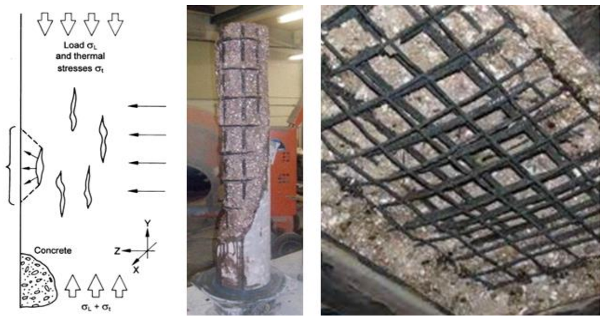

Fig. 13. Spalling failure mechanism of concrete and concrete failures on column and slab by spalling during fire

The sagging and buckling failure of structural steel and induced by creep and relaxation phenomena at elevated temperature are occurred around 500~600℃ shown in Figure 14. The stability of structure for both concrete and steel even though composite structure is critical when a temperature increased while without change of the fixed loads such as dead loads and live loads during fire event.

Fig. 14. Typical sagging and creep failure of structural steel

6. Conclusions

The meaningful first step for developing the structural fire integrity in nuclear power plant building is started with the series of fire related sub sections mentioned in earlier section. The recognition and sufficient effort of fire research leads to set up the safe and reliable design of nuclear power plant.

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