Introduction

Fire damage to structures, cost more than a few billion dollars each year for the owners and insurance companies. Although majority of this cost is paid back to the construction industry and associated professions, there is surprisingly very little amount of globally published material available for the everyday practice.

The case study report here is prepared to share the story of the study carried out last year, [1], [2], by the ERDEMLI-ITU team and to discuss the lessons learned from the fire event in our case.

The Structure

The 4-storey reinforced concrete structural system was built in 1968 and is simply composed of 6m×8m beam-slab system with 6m×9m long slender columns. (Fig.1)

Although the site is within 15 km neighborhood of a major fault mechanism, due to the age of the structure and the original seismic design code used, base shear capacity is almost %25 of the current code requirements.

The cover concrete thickness is 5 cm for the columns and 3 cm for the beams and slabs. Original construction materials are concrete with compressive strength of 20MPa and reinforcing steel with the yield strength of 420MPa.

Capacity of the plant was three times updated since the original design and the existing service load is over 1500kg/m2 (even 3000kg/m2 for some slabs). Heavy industrial piping exists and there is almost no free space to walk through the building due to the existing piping and equipment.

Reactors, chemical storage tanks and other buildings, which are undamaged but have to continue operation due to their key importance on the non-stop production requirement, occupy the neighborhood of the damaged building. (Fig.2)

The Fire Event

The fire started due to an accident, which took place in the reactors around the building and
developed very fast, lasted more than 3.5 hours reaching the maximum temperature over 680oC according to the external fire curve. (Fig.3)

Fig.3: Typical fire curves

As the source of the fire was continuous, the surrounding gas temperature did not fall down and was almost constant for the whole event, which means the real fire curve at site was very closed to the one given in the figure.

The flames followed the equipment and service holes on the slabs, and moved up to the roof level, where they left the building after damaging all the floor levels. (Fig.4)

Fig.4: Holes on the RC slabs that the fire traveled through and has extensively damaged.

Primary, reinforced concrete elements had a wide damage distribution from cosmetic damage to severe structural damage. A few columns had exposed reinforcement, and most of the beams and slabs were heavily cracked. In some places their reinforcements were partially exposed.

The secondary structures constructed by steel, as t-posts, interior pipe racks and steel platforms have failed during the fire event. (Fig.5)

Fig.5: All deformed piping and connections to neighbor structures that have failed due to the surrounding gas temperature during the fire event.

With the joint effort of local and neighbor fire departments in the area, the fire was controlled totally, after a few hours of extreme effort.

The Need

Due to the key importance of the plant in the overall production chain and the ‘cost of each minute’ case, client came with the rapid inspection and damage report need.

Decision making was needed in the shortest time possible, in order to quickly take the necessary precautions, move the undamaged equipment in the building out and than go on with the chosen option of either demolishing and rebuilding, or repairing and using the same structure to the extent of the building’s economic life.

Performance expectations were defined under service/ultimate loading conditions for the rest of the service life.

Visual Inspection

Starting the study at site, the team first activated a group of experts on fire damage and carried out a detailed visual inspection on the building.

Visually surveying the structure, the experts marked every beam, column and slab on the plan sketches with damage classes from C-0 to C-4 according to the details given in Table-1 given below. [3]

Table.1: Damage class definitions. (Table reproduced from Concrete Society Technical Report No. 33)

Material sampling locations to indicate similar material damages along the building were decided and marked on the structural elements taking the same damage classes as basis to define the structural and material damage levels.

Material Sampling

Definition of the original undamaged and damaged material properties is the basic step of correct analysis of damage extent on the structure.

Keeping this in mind ERDEMLI-ITU team carried out a site study to take material samples (core specimens) of previously defined structural elements and to make ultrasonic pulse velocity readings on similarly damaged structural elements. From all levels of the building, indicating different damage class elements, a total of 24 material samples were taken and 50 readings were recorded at site.

Reinforcing bar samples were taken from a few locations where the bars were exposed and buckled, from concrete spalling zones and from less damaged cracked zones. (Fig.6)
Loading Information

Equipment weights, operating loads piping loads and support loads for equipments and industrial piping in the building were listed and client documents were converted into structural load lists.

Special attention was given to fire damaged structural elements carrying comparatively larger loads to the others.

The team and the client prepared a to do list to be used during unloading and this unloading stage list was also taken into consideration while unloading and reloading stages were defined for the structural analysis.

Laboratory Study

Within the frame of the lab experiments on the material samples taken from site, the team investigated a model relation to define the correlation between the core specimens and material states at site on structural elements.

After the lab experiments [2] on core specimens, a model relation of concrete strength vs. ultrasonic pulse velocity was defined. (Fig.7)

![Fig.7: Model relation to be used for correlation between the site measured values and estimated concrete strengths.](image)

To follow the changes on material properties from the outer surface, to the core of the structural elements, sample measurements of the material properties were made, on each layer of the specimens. (Fig.8)

![Fig.8: Damage path to the core of concrete section.](image)

Using the model that was developed for the experimented specimens damage map on the structural elements were prepared in terms of concrete damage and composite strengths.

Office Study

A number of finite element nonlinear section analysis were carried out with different layers of damaged and non-damaged concrete material properties, to define the composite section properties.

Strengths, stiffness and ductility properties of typical damage classes were listed for being used in fast elastic analysis of the whole structure.

A first stage 3D finite element structural model of the structure was built by a structural design software to see the actual original state of the structure and the undamaged structural performance under defined loading conditions. (Fig.9)

![Fig.9: 3D Structural Model](image)

Using the damaged material and section properties and the loading information, a second 3D structural model was created to see the performance of the structure, with the real damaged state material properties.

The two results were compared and damage classes on all structural elements were graphically presented to show the major damage distribution along the structure. (Fig.10)

![Fig.10: 3rd Floor damage distribution on slabs and beams. (Red-Class4 to Blue-Class0)](image)

Rehabilitation Proposals

As the major aim of the study was decision making to either rehabilitating the structure and reoccupying it, or demolishing the structure and rebuilding a new one, a two option cost analysis taking into account the cost of time spent during each option, was carried out.

For rehabilitation of the damaged structural elements a typical rehabilitation method for each different damage level was identified and cost analysis was done accordingly. [4]

The proposed methods to repair the concrete elements are listed in the Table-2 below.

Table.2: Repair class definitions.
Results of the study have shown that rehabilitating the building and reoccupying it, although was comparatively more expensive, was the only option fast enough, to keep the time schedule required for re-operation of the plant.

**Conclusion**

Analyzing the extent of damage and distribution of it throughout the building and structural elements, ERDEMLI-ITU team marked some major items to be shared by the readers.

- Fire is a very high probability hazard that should be considered while detailing industrial plants.
- The structural and non-structural performance of industrial plants under possible fire events should be clearly defined by the client, to be taken as basis in the design progress.
- For reinforced concrete structures, concrete cover thickness on reinforcing bars has extreme importance, as the extent of damage, on material properties of concrete decreases from surface, to the core of structural elements. In our case, the 5cm cover in columns protected columns more than the beams-slabs with 3cm cover and by this way a possible collapse mechanism did not come out although the columns were heavily damaged.
- Upper halves of columns were more heavily damaged than the lower halves, so it is strongly recommended that the core specimens or readings at site should be taken from higher positions of columns, although it is not an easy practice.
- In defining the composite residual strengths of the structural elements that were exposed to fire hazard, the undamaged zone in the core of structural elements should be carefully modeled, (especially in columns) so that the damage distribution on the structural elements can be better understood and the engineers can better interpret the possible distortions and deflections.
- We underline the importance of preparation of detailed damage maps, for all levels involved in the fire, with all structural elements within the damage range, so that a well-defined structural model can be prepared and the cost analysis can be based on better and more precise calculation model.
- The cost of “off-time” spent for rehabilitation or rebuilding should be included in cost analysis, as its influence on most industrial applications is enormous.

**References**


