Evaluation and Repair of Construction Damage to an Old Factory Building

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Abstract. This paper describes the performance based seismic rehabilitation of an old four-story RC frame building which is being remodeled to be reused as an office building in the creative industrial park. The building is part of the city's adaptive reuse and redevelopment program. It was designed and constructed in the 1980’s and, therefore, does not meet current design and detailing standards. To make matters worse, two of the first floor columns were badly damaged during renovation and were in danger of collapsing at any time. This paper presents the effects of the accident, failure mechanism, as well as the actions taken to repair the building. The damaged columns are strengthened by a reinforced concrete jacket. The beams closer to damaged columns are retrofitted by externally bonded CFRP. Structural redesign made it feasible to rehabilitate and strengthen the structure sufficient to meet seismic criteria that were judged to be compatible with the site conditions.

Keywords: Seismic evaluation, failure mechanism, retrofit, strengthening, RC jacket, CFRP reinforcement.

1. Introduction
With the upgrading of industry and the change of urban development strategy in recent years, many large enterprises have been relocated and transformed. Reconstruction with a change in the functional purpose of buildings can save on expensive demolition and new construction, and at the same time, it is beneficial to the sustainable development. The subject of this paper is a case study that involved columns construction accident of an old factory building under renovation. According to the evaluation, the design idea and strengthening methods are put forward.

2. Background and Description
The metalworking assembly building was built in 1987, which originally housed metal workshop. After being vacant for several years, the old building was rented by a developer with an eye to renovating it for high-end office use in the creative industrial park. The building is rectangular in plan and measures approximately 84.64 m in the east-west direction and 18.0 m in the north-south direction. It is a four-story RC frame building with seven-story of masonry structure at both ends, as shown in Figure 1. It is representative of old types of buildings designed in the early 1980s based on aged approaches and code provisions. There is a mezzanine floor at axes 3-10/B-C of the structure between the first and second
level. The interstory heights are 6.4 m for the first (including 1.8 m for the mezzanine), 5.70 m for the second and third floors, and 5.0 m for the fourth floor.

The structure consists of cast-in-place reinforced concrete beams, columns, and floors. The mezzanine floor is prefabricated hollow slab. The thickness of the cast-in-place slab is 100mm and 120mm. The typical beam spans are 9 m in the transverse direction and 6 m in the longitudinal direction. Beam widths and depths ranged between 250–300 mm and 600–900 mm, respectively. The plan dimension of side column is 400 × 600 mm and of middle column is 450×700 mm with an effective cover of 20 mm.

![Figure 1. Plan view of case study building.](image)

3. Evaluation of the Existing Building
The field survey results show that the available blueprints of the considered buildings obtained from the project owner are generally in good agreement with the existing layout of structural components with their dimensions, which can be used as the main basis for the reconstruction design.

But, there are several defects in material properties obtained in the field are not compatible with the strength shown in the blueprints of the buildings. In the blueprints, the concrete strength (fc) is 28MPa. According to standard requirements, a minimum of three samples of concrete cores and reinforcing steel were extracted from the various structural components and tested. Moreover, the final testing result shows that the concrete strength (fc) varies from 22MPa to 25MPa. Furthermore, as a general rule, this kind of buildings were designed and constructed in the 1980’s and, therefore, does not meet current design and detailing standards.

4. Construction Accident
4.1. Description of the Damaged Columns
According to the initial renovation scheme, this building will be changed into high-end office space. The original starting point of the design is to retain and carry forward the large space sense, and the final decision is to remove mezzanine in the first floor. Unfortunately, due to the wrong construction procedure and improper construction control, two of the first floor columns (7/B and 8/B) were severely damaged during the renovation, especially column 7/B as shown in Fig. 2(a).

At that time, the construction team did not dismantle the beam-slab structure in accordance with the conventional process. Before demolition, no separation joints were set at the end of the beam 7/B-C, and the longitudinal bars of the beam were not cut off. It directly led to the frame column suffered from large shear force and bending moment at the beam-column joints of the mezzanine floor. RC columns may experience complex combined shear, bending, and torsional loadings. The resulting apparent damage included cracking or spalling of concrete cover, crushing of the concrete core, and buckling of reinforcement (see Fig. 2(b)).
4.2. Effect on the Adjacent Components
The accident caused the brittle failure of two neighboring columns and damaged some of the beams in the immediate vicinity. Fig. 2(c) shows the cracks at bottom and side of beams adjacent to damaged columns. Cracks at bottom and side of beams are nearly connected to become through cracks. The maximum crack surface width is about 0.1mm, extending from the bottom to the middle of the beam side.

In addition, the related components on the second floor closer to damaged columns are also affected in different degrees. The column 7/B on the second floor has a circular crack with a surface crack width of 0.05mm at a height of 800mm from the floor. Both transverse beam 7/A-B and longitudinal beam B/6-7 on the third floor have cracks near column 7/B, and the width of cracks is 0.1mm. According to the deformation of the broken column, the cracking of the beam and the measurement results of the relative height difference, it can be obtained that the additional deflection of the intersecting beam at 7/B caused by the broken column is less than 10mm.

4.3. Possible Problems and Consequences
On the basis of the definition given by Lehman et al. (2001), visible evidence of core concrete crushing, longitudinal bar buckling, or longitudinal/transverse reinforcement fracture is classified as severe damage. The most severe damage is associated with column failure or imminent failure. The failure of columns structure contributes to the serious consequences in structural stability. Under the circumstances, the structure may be vulnerable to progressive collapse, which begins when a load-bearing member suddenly loses its ability to carry the loads above it. Once this happens, the failure can propagate through much or all of the structure if there is insufficient redundancy and continuity.

Several recent engineering accidents have indicated that buildings designed and constructed based on older seismic design provisions are vulnerable to catastrophic collapse resulting from the failure of columns. To avoid similar accidents, the construction team set up temporary supports at the bottom of the beams around the damaged columns as soon as possible, as shown in Fig. 2(d).

Figure 2. Damage views of building following the construction accident: (a) view of damage columns; (b) buckling of longitudinal reinforcement bars, concrete spalling and dis-integration (column 7/B); (c) cracks on beam 7/A-B; and (d) temporary supports. (Images by Huabo Liu.)
4.4. Analysis of Failure Mechanism

In the initial stage of column failure with small vertical displacement, the primary resistance to gravity loads is provided by the flexural action of beams (for the frame with continuous reinforcement). The original integral frame structure loses the middle fulcrum, and the end of beams closer to damaged columns at second floor changes from the original compression area to the mid-span tension area. The cracks radiated out from column 7/B and the through cracks at the ends of beams closer to damaged columns implied the formation of internal force redistribution. Additionally, the failure of two columns in the lowest level of a multistory building also leads to the formation of cracks in column 7/B on the second floor and beams on the third floor. It provides more proofs about the formation of catenary action. The beam catenary mechanism can be considered as an alternative load path and can resist additional loads. As the beams undergo larger deflections, the load-carrying capacity of the frame will be lost due to the fracture of reinforcements until the catenary action in beams utilizes the tensile force to balance the vertical applied loads as the last defense mechanism.

5. Retrofit Design

The column failure can trigger the progressive collapse of building structure. To prevent such catastrophic losses and strengthen the seismic performance, rapid repair methods are needed to temporarily restore a certain level of function and prevent damage from extending to other regions. Hence workers immediately erected scaffolding as temporary support around the damaged columns after the accident happened.

5.1. Unloading

Before reinforcement, to ensure return to the original state of the components, it is necessary to set up reliable supports around the damaged columns and under the beam. The two ends of the steel pipe are welded with steel plates, which are connected with the beam to ensure the overall stability of the system. A jack is arranged at the lower part of the supporting steel pipe. The jack is raised to make contact with the bottom of the steel plate, and incremental uniform load was applied to unload. Cracked beams and adjacent slabs were successfully jacked back into original positions by a construction procedure that employed the use of scaffolding together with the hydraulic jack.

5.2. Substrate treatment

The repair of the columns began by removing any loose concrete from the columns at the beam-column joints of the mezzanine floor. Repair procedure: (1) chisel away loose concrete from the damaged area; (2) clean column prior to repair; (3) restoring of cross section with patching material; (4) epoxy injection of cracks.

5.3. Column Strengthening

Jacketing technique has been commonly used for column and beam strengthening. A retrofit using concrete jacketing is an effective method for restoring and enhancing the structural stiffness and the bearing capacity. In this case, concrete jacketing was done to strengthen the damaged columns. Holes were drilled in the foundation beam to half its depth and additional longitudinal reinforcements were inserted near the existing reinforcements and was grouted with 1:2 cement grout. Planting bars are used at the upper end and the side of the column. The additional longitudinal reinforcement was properly joined to the existing reinforcement. Due to columns with shear capacity less than the demand required by recent seismic codes and columns with inadequate lap splice detailing at column-to-footing connections, shear reinforcement was provided in between the existing shear reinforcement such that their spacing was reduced by 50%. The section was finished by the addition of concrete jacket of 80 mm thickness.
5.4. Beam Strengthening
The beams closer to damaged columns would be retrofitted by externally bonded CFRP. Two layers of CFRP bonded at the bottom of the whole beam. The vertical U-shaped CFRP sheets were then applied followed by the installation of a mechanical end anchorage. The U-shaped CFRP sheets had a width of 200 mm and a center-to-center spacing of 400 mm. In order to provide anchorage and support for these U-wraps, longitudinal CFRP strips were installed along the top for anchorage.

6. Conclusions
Sensible retrofit and renovation is an extremely impactful strategy that can be done to achieve sustainable design goals. The biggest challenge in any retrofit procedure is that the engineer must deal with an existing structure, which in most cases has not been designed in accordance with current building codes and regulations. Structural damage due to construction defects, fire, vehicle impact, seismic or wind loads further complicate retrofit scenarios.

This paper presents a case study of seismically retrofitting an old factory building located in Shanghai. After the retrofit, the four-story metal workshop will be transformed into high quality, creative office space. All structural modifications made since the building was originally constructed using very low strength concrete were considered in the evaluations and retrofit design. However, it suffered unexpected damage to the extent during renovation that continued use requires redesign and additional repair. Due to the high risk of collapse posed by construction accident to existing substandard structures, investigating and developing effective seismic retrofitting methodologies particularly for such buildings becomes a vital topic.

It is important to obtain accurate as-built information and on-site data to perform a seismic evaluation of the old factory buildings and to select the appropriate retrofitting strategy. As for structural performances, not only the knowledge of the actual capacity is necessary, but also whether damage level allows the existing structure to handle a renovation process has to be determined. This case study has hopefully demonstrated that, with prompt treatment and careful design, these retrofit techniques are effective and can improve strength and ductility of the structure simultaneously so the building can withstand earthquake motion as demanded.

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