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Case Study of Structural Cracks in Irregular RC Tall Building During Construction

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Abstract

Structural cracks happen during construction of RC buildings due to various reasons but they are more often considered as construction faults rather than being considered as mistake or misassumption in structural design. This study presents an example of development of several types of cracks during construction of an irregular tall building. After collaborative investigation by site and research teams of the Project's General Contractor based on the result of construction stage analysis, the cracks – especially the most severe ones developed in the perimeter girders under slanting columns – were identified to be caused by the accumulation of vertical load due to progression of construction. Appropriate corrective measures were taken to repair the cracked members without interrupting scheduled construction. The lessons learned in this case study exhibit that elaborate staged analysis considering actual sequence of construction is vital for the design and construction of irregular RC tall buildings.

Keywords: Building Movement; Construction Stage Analysis; Slanting Column; Structural Crack; Structural Reinforcement; Strut-and-tie Model

This paper investigates identified cracks during construction of an irregular tall building with complex structure, which is referred to as the Tower hereafter. Causes of the cracks are analyzed from the survey of current condition of crack development and the study of the Tower's structure related with construction sequence. Proposed methods of reinforcement and repair and final decision are then presented to make the Tower's structure recover its structural safety, serviceability and durability.

Project Overview

The Tower is 298 m above ground with 64 floors. The structural material is mostly a reinforced concrete with minor usage of steel. A rectangular core area is eccentrically located inside a diamond-shaped plan bounded by perimeter girders and mega columns. Construction of the Tower's structure and façade is almost complete as of June 2015 and it will be used for offices, a hotel and high-class residential.

As is inferred from the elevation in Figure 1, the Tower is not an ordinary rectilinear tall building where gravity load on the floor slab is first transferred to beams and/or girders and then through columns and/or wall finally to the foundation. The Tower has six mega columns interconnected with mega diagonal members called "slanting columns" roughly at every 10 floors interval. Tower columns located between the mega columns transfer the gravity on the floor slab to the slanting columns, which then transfer the load to the slanting-mega column joint by truss action. That's why the tower columns are discontinued below the slanting column at Levels 13 and 16 as shown in Figure 1. However, until each slanting column is constructed and fully connected at the slanting-mega column joint, the massive weight of the slanting column needs to be supported by the tower columns called "dummy column".

Crack Locations

The cracks have occurred in perimeter girders, soffit of floor slabs and side surface of beams connecting perimeter girders and core walls as listed below and shown in Figure 1. These cracks are most severe at Level 16.

- Perimeter girders under slanting column and dummy column position: Levels 13, 16, 22, 25, 31, 34, 45 and 48. At first, only the cracks in Levels 13 and 16 were reported and the rest were identified by thorough investigation of the structure
- Floor slabs: from Levels 10 to 17

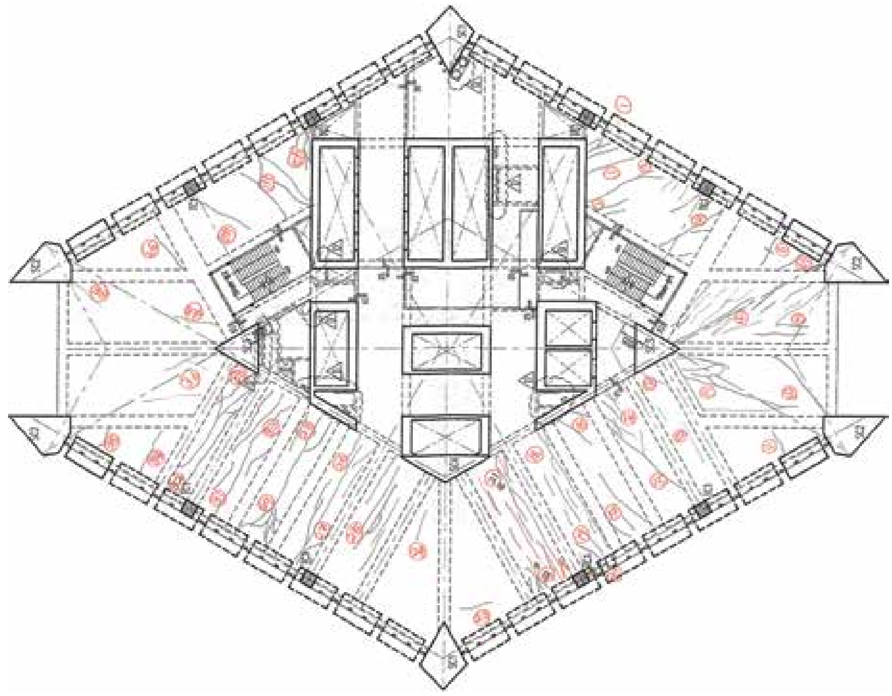


Figure 3. Map of cracks on the soffit of floor slab at Level 16 (Source: Daewoo E&C)

Figure 2. Diagonal shear cracks and vertical flexural cracks in perimeter girders under slanting column and dummy column location at Level 16 (Source: Daewoo E&C)

- Other perimeter girders and beams connecting perimeter girders and core walls : same locations as the cracks in the soffit of floor slabs

Crack Patterns and Developments

Perimeter girders under slanting column and dummy column location

Large inclined cracks connecting the diagonal opposites of the girders exist with a series of vertical cracks under the girder (see Figure 2). The direction of the inclined cracks start from the joint of the girder and the slanting column (STC) and end at the joint of the girder and the tower column (TC). Although not shown in the figure, surface cracks are also found on the floor slab above in the location of TC. This is one of the typical crack pattern of a reinforced concrete beam or girder, especially with short span ratio (= span vs. depth), when it is overly stressed.

The following is the simple description of a girder with this type of crack:

As a load on a girder increases, the first flexural crack appear at the bottom of the girder if the applied moment reaches the cracking moment (Mcr) of the girder. This flexural crack develops in the vertical direction as the load increases and, at the same time, additional flexural cracks appears adjacent to the first crack. The new flexural cracks are not perfectly vertical but start to be inclined in the direction which connects the loading area and the support area. After the load path from the loading area to the support area is established, the inclined cracks get wide open and interconnected each other until structural failure of the girder happens.

Of the four pairs of girders in each STC span, the girders located at upper levels are more severely affected by this mechanism of crack development, since they have a smaller span ratio than that of the girders at lower levels. For example, the cracks in the girders at Level 16 is more severe than those in the girders at Level 13. Actually, the cracks in the girders at Level 13 stay as vertical flexural cracks and do not develop into the inclined shear cracks. This tendency remains the same as STC spans move up along the building elevation with diminishing severity in the crack development. For girder at higher levels of the Tower, most of the inclined cracks disappear (see Table 1).

Floor Slabs

The cracks exist only on the soffit not on the above surface of the slabs outside of core walls. No crack is observed in the slab inside the core walls. As shown in the crack map in Figure 3, these cracks generally radiate from a core location in the direction of beams to the perimeter girders: most of the cracks are parallel to the beams but are deviated as they approach to locations of four SC2 mega columns. This pattern of cracks may happen when the slabs are in tension in the circumferential direction in the Tower's plan. Some cracks are connected with the cracks in the perimeter girders as shown in Figure 4.

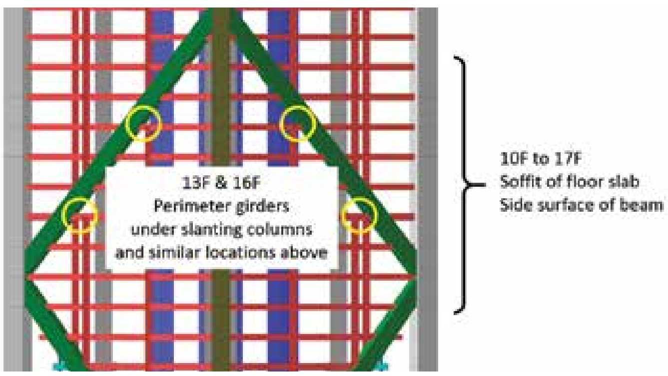


Figure 1. Crack locations marked in building elevation (Source: Daewoo E&C)

STC span	Grid	A1-A3	A6-A8	B1-B3	B6-B8
	Level	Type of cracks (F: flexural, S: shear)			
11F-19F	13	F only			
	16	F and S			
20F-28F	22	F only			
	25	F and S			
29F-36F	31	F only			
	34				
43F-51F	45	No crack		F only	
	48	No crack	F and S	No crack	

Table 1. Type of cracks in perimeter girders under slanting column and dummy column location (Source: Daewoo E&C)

Figure 4. Cracks on the soffit of floor slab at Level 16: cracks in non-rectangular slab (above) and slab cracks connected with cracks in a perimeter girder (below) (Source: Daewoo E&C)

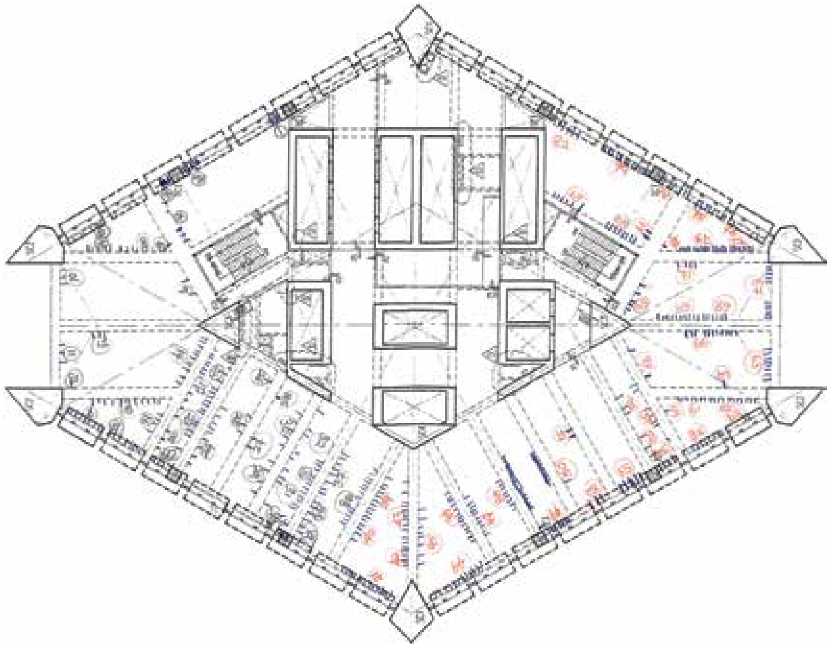


Figure 5. Map of cracks in perimeter girders and beams connecting perimeter girders and core walls at Level 16 (Source: Daewoo E&C)

Other Perimeter Girders and Beams

These cracks occurred on the sides of the girders/beams in a vertical direction and are generally evenly distributed along the length of the girders/beams. The crack width is constant along the crack length.

Cracks exist in most of the perimeter girders except for ones bound by STCs and TCs, and ones near SC1 mega column and core walls as shown in the crack map in Figure 5. These cracks exist on both sides of girders and are not seen on the bottom face. However there are some exceptions. The direction of the cracks generally coincide with those on the soffit of the floor slab. These cracks deem to have the same mechanism of cracking, i.e. circumferential tension in the Tower's plan. Also, the cracks in the perimeter girders are generally more closely spaced than the cracks (compare the two photos in Figure 6).

Cracks in beams under floor slabs are similar in pattern and degree of development to those in perimeter columns but differ in the overall orientation of development in building plan. Their orientation is orthogonal to that of cracks in perimeter girders. Considering the orientations of the beams, these cracks may develop if the beams are under tension in the radial direction of the Tower's plan.

Construction Stage Analysis

To identify the structural conditions of the cracked member as the construction progresses, a construction stage analysis was performed based on the actual construction schedule. This analysis is the same as the one that was the basis of the Tower's movement control but the analysis at that time focused on the evaluation of the axial shortening and deviation from verticality of the Tower (see Figure 7). This time, the variation of internal forces, i.e. axial force, shear force and bending moment, are obtained as the results of the analysis for perimeter girders and beams, but not for slabs. The state of in-plane stress could be inferred from the axial forces in the bounding girders and beams.

Advanced Stage Analysis Program (ASAP)

Construction stage analysis is available in various commercial structural analysis programs including SAP 2000, MIDAS/GEN, SOFiSTiK, LUSAS, GSA, and Scia Engineer. They were originally developed for the construction stage analysis of bridges but have evolved to be applied to tall building analysis. The construction stage analysis for tall buildings were mainly focused on column shortening analysis beginning in 1970s in US (Fintel 1986). The deformations in columns and walls were calculated by isolating them from the whole building and the amount of deformations are usually divided into UPTO (up to slab casting) shortening and SUBTO (subsequent to slab casting) shortening based on the construction of respective floors. The famous structural design firms had their in-house program to perform column shortening analysis.

As more tall buildings are constructed worldwide and problems related with building movement are identified, the focus has shifted from structural viewpoint to construction and maintenance ones. This shift came from observation of actual phenomena in the existing tall buildings.

Figure 6. Cracks on the side of perimeter girders (above) and beams connecting perimeter girders and core walls (below) at Level 16 (below) (Source: Daewoo E&C)

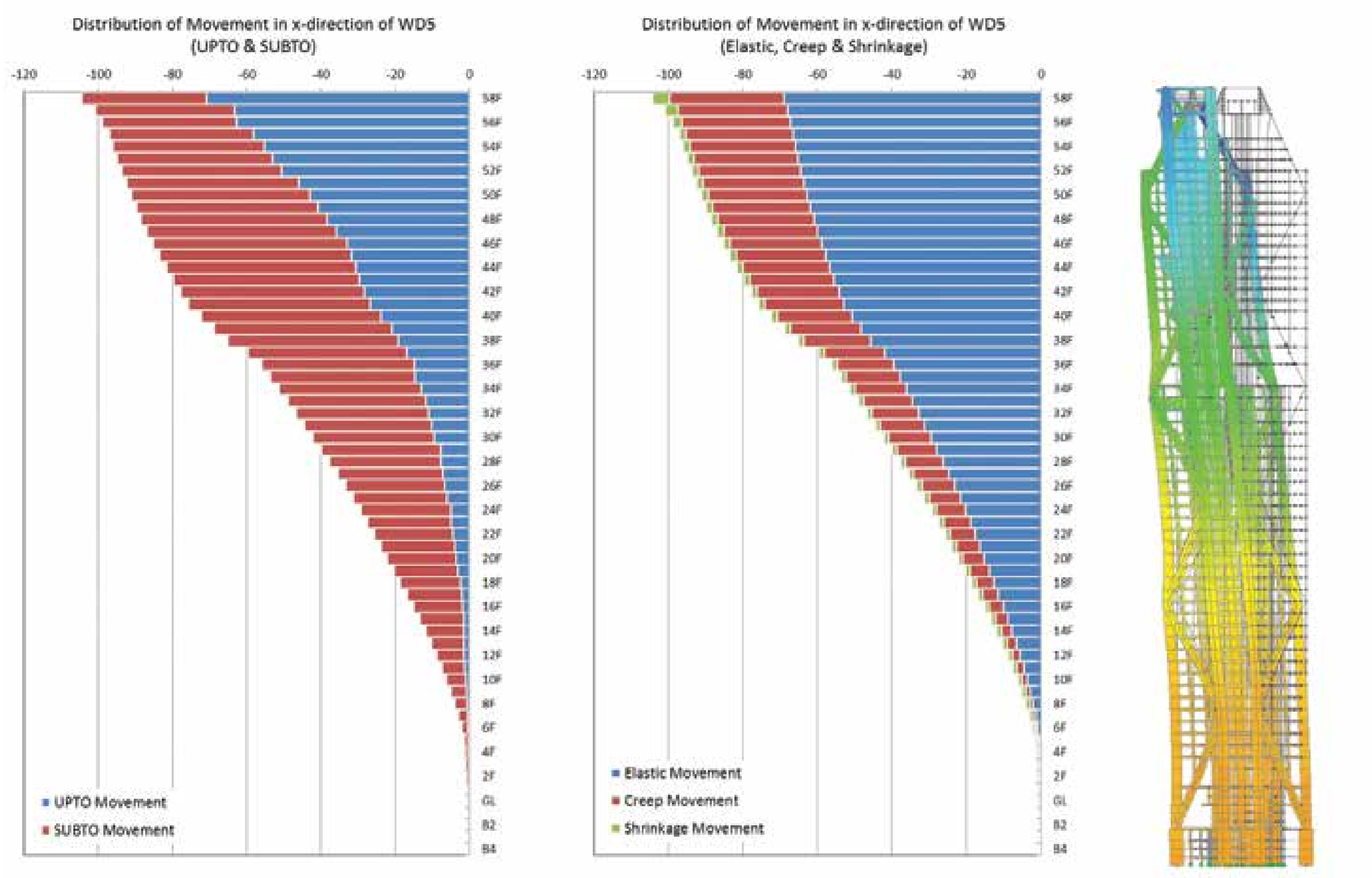


Figure 7. Results of construction stage analysis of the Tower regarding deviation from verticality (Source: Daewoo E&C)

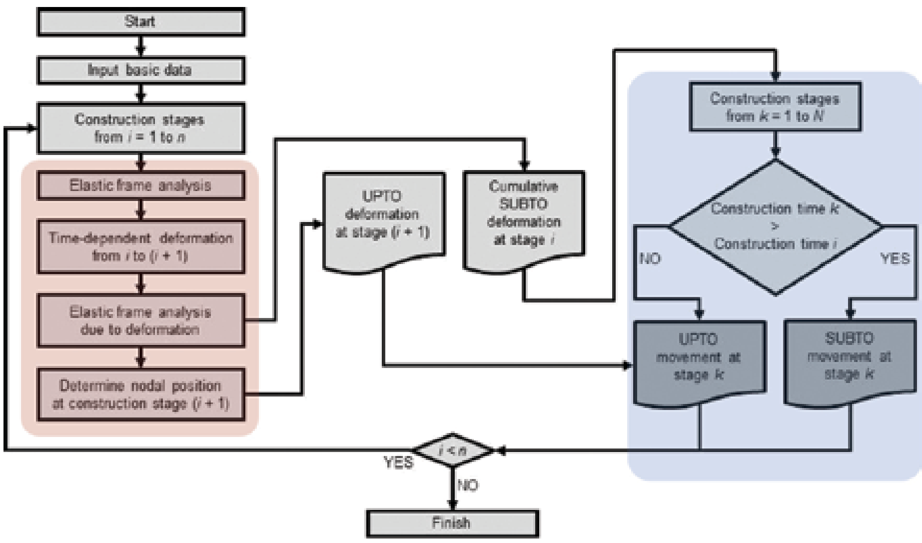


Figure 8. Algorithm of Advanced Stage Analysis Program (Source: Daewoo E&C)

The misalignment of slab levels with vertical pipe shaft and dismantling of elevator rails from brackets on elevator core walls are some representative problems due to building movement in the axial direction (Bast 2007). When the movement occurs in lateral direction, verticality of the elevator cores is impaired even before the installation of elevators. According to documents from actual construction of a famous tall building, the authors have identified design changes in elevators to accommodate its installation within the reduced projected area of elevator core. On the other hand, structural problems due to locked-in forces developed from differential movement of adjacent members are hardly recognized except for members with high stiffness such as outriggers and belt walls. Most of the locked-in forces can be assumed to be redistributed in the course of construction.

Construction and maintenance problems related with building movement could be prevented when the detailed process of building construction is considered. When most tall buildings are designed and constructed as rectilinear, the problems are caused by the deviation from the horizontal or vertical datum line for each construction items such as floor finishing, elevators, façades. Therefore, construction stage analysis should also focus on the time of construction of these items even if significant loading is not applied at that stage. It can be done by adding additional staged analysis after SUBTO (subsequent to structure construction) deformation is calculated as shown in Figure 8. This patented feature is still not available in aforementioned commercial programs but first implemented in Advanced Stage Analysis Program (ASAP) developed by authors'.

The program creates or imports 3-dimensional structural model of a building for analysis. The user defines the time-dependent properties of concrete such as modulus of elasticity, creep, and shrinkage according to ACI 209, 318, and 363. Other creep and shrinkage models such as Eurocode 2, B3, and GL2000 were also incorporated into the program for a possibility of better prediction of building movement (see Figure 9). The amount of reinforcement can also be input to consider the effect of load redistribution between steel and the surrounding concrete for RC and SRC members. The construction sequence of a building is modeled by assigning birth date or extinction date to each element of the structural model for self-weight and to other additional loading stages. In the process of analysis, the model is analyzed at each construction stage for member forces and

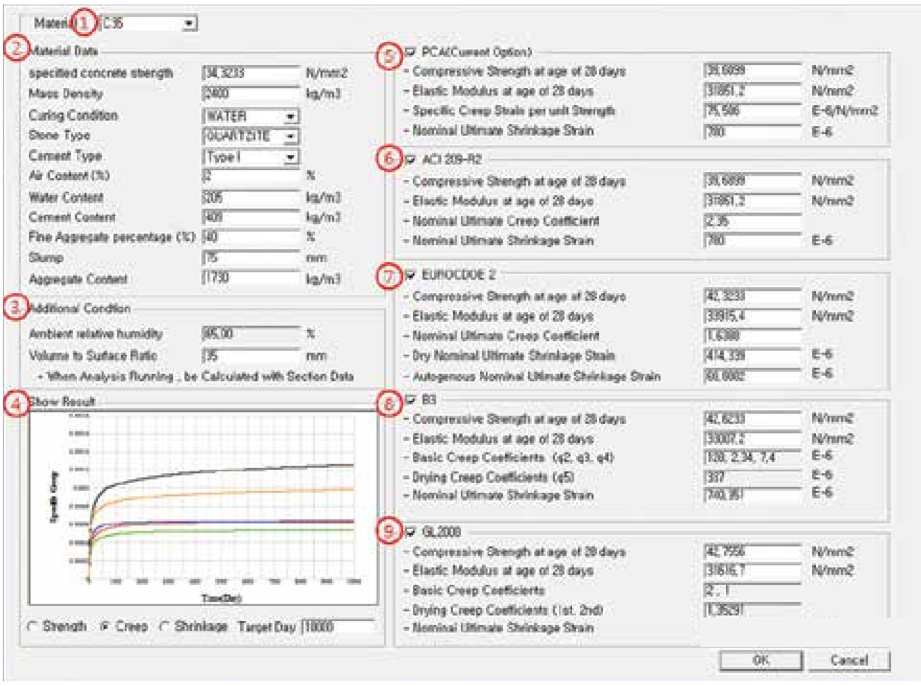


Figure 9. Input window for time-dependent properties of concrete in ASAP (Source: Daewoo E&C)

deformation, and the intermediate results are stored and used as datum values for the next construction stage analysis. As a result, the building is simulated for its movement and forces for all stages of construction. As shown in Figure 10, the movement of a building can also be exhibited at every construction stage for visual review and inspection.

Result of Construction Stage Analysis

Figure 11 shows the variation of member forces, i.e. axial and shear forces and bending moment for the perimeter girder bounded by STC and TC at Level 16. The x-axis spans more than 4 years from the actual construction date of the member until the target time of the construction stage analysis, which was set at 3 years after the completion of construction. All the member forces except for axial force show ever-increasing tendency until the target time. Expected shear force in the girder has already reached its design capacity on the date of removal of the dummy column. Positive design moment on the tension side of the girder was also surfaced by the developed moment before the cracks were identified. Considering the basic function of beams and girders, this phenomenon deemed abnormal under gravity-only load condition.

The comparison of required and designed member forces for the perimeter girders under similar structural configuration is summarized in Table 2. The bending moment and shear force in some of the perimeter girders that have cracks already have exceeded the designed resistance of the member under the loading conditions during construction (1.0D + 0.5L) or shall have insufficient capacities compared with the requirements for the structural safety.

Identified Causes of Cracks

As evident from the result of construction stage analysis, the causes of the cracks are identified as the progress accumulation of vertical loads from above during construction, which was not captured properly at the design stage.

For perimeter girder bounded by STC and TC, all the vertical load from levels above are transferred via STC to TC solely by the girder. This is because the dummy column above was removed after the construction of STC span had been completed. In an ideal condition of truss action, all the vertical load from the STC should have been transferred in axial direction of the STC to the joint of STC and mega columns. However, the STC also exhibited flexural action, which in turn exerted vertical load on the perimeter girder. This load gets greater as the construction progresses and eventually makes the girder crack. In case of the girders at upper levels of each STC span, this mechanism of load transfer is made directly from STC to TC due to the girder's smaller span ratio – less than 2.0 – that the initial flexural cracks have developed to severe shear cracks as shown in Figure 12.

If this load were to be captured at the design stage, these girders should not have been released with hinges at both ends as usually done when high concentrations of internal forces are encountered during the structural analysis. Instead, more elaborate analysis and design are required considering the cumulative nature of the load and the mechanism of direct load transfer. It can be done by a sequential application of the construction stage analysis for applied load and the so-called strut-and-tie model for member design.

Although being under similar loading condition, the girders at lower levels of each STC span have a longer span ratio – more than 3.0 – that the load is transferred by typical beam action, i.e. flexural behavior. This is the reason why no inclined shear crack is observed in the corresponding girders. Those girders have only flexural cracks under the bottom and/or on the top surface.

Except for the perimeter girders mentioned above, all the other perimeter girders, floor slabs and beams from Levels 10 to 17 exhibit cracks showing as if these structural members are under tension. This can be explained by the in-plane tension in the building plan due to the diaphragm actions exerted by the combination of slabs, girders and beams in the plan.

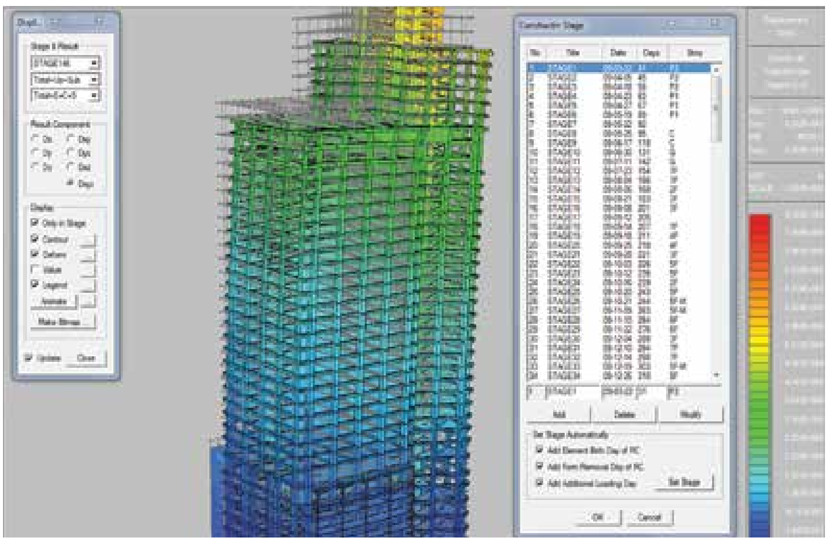


Figure 10. User interface of ASAP (Source: Daewoo E&C)

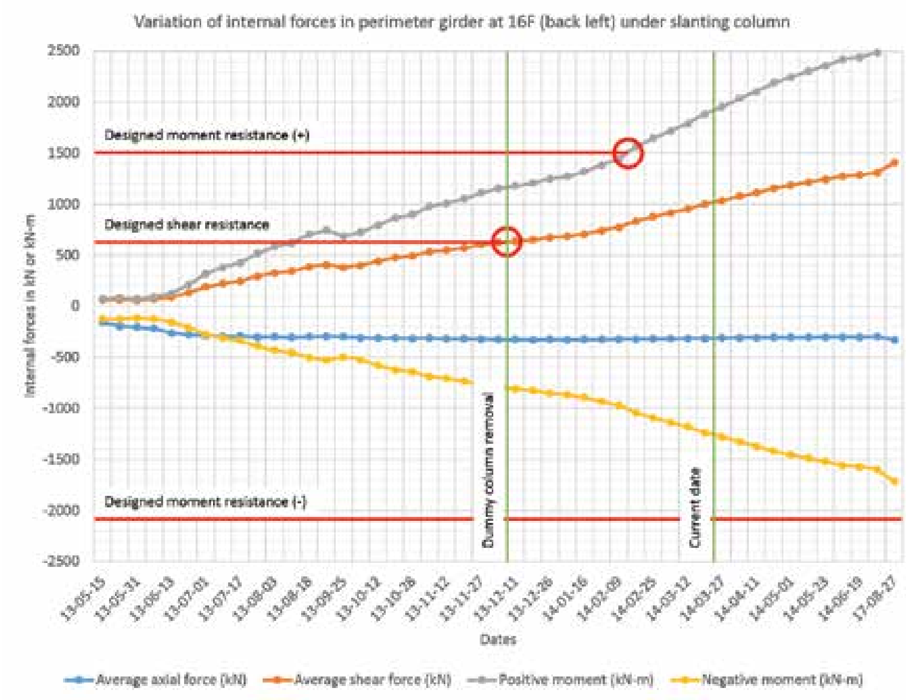


Figure 11. Variation of internal forces in the cracked perimeter girder at Level 16 (Source: Daewoo E&C)

Girder name	Positive moment (kN-m)		Negative moment (kN-m)		Shear force (kN)	
	Required	Designed	Required	Designed	Required	Designed
L13B1	**3140**	1670	-1245	-2103	**1597**	1061
L16B1	**2674**	1495	-1715	-2103	**1433**	616
L22B1	660	2315	-931	-2315	429	1284
L25B1	543	1495	-352	-2103	272	616
L31B1	362	2315	-300	-2315	246	1284
L34B1	1089	1495	-1013	-2103	**641**	616

* The required moments and shear forces were obtained from the loading condition during construction (1.0DL+0.5LL) and includes the long-term effect (creep and shrinkage) until 3 years after the completion of construction.

Table 2. Comparison of requirement and capacity of selected perimeter girders (Source: Daewoo E&C)

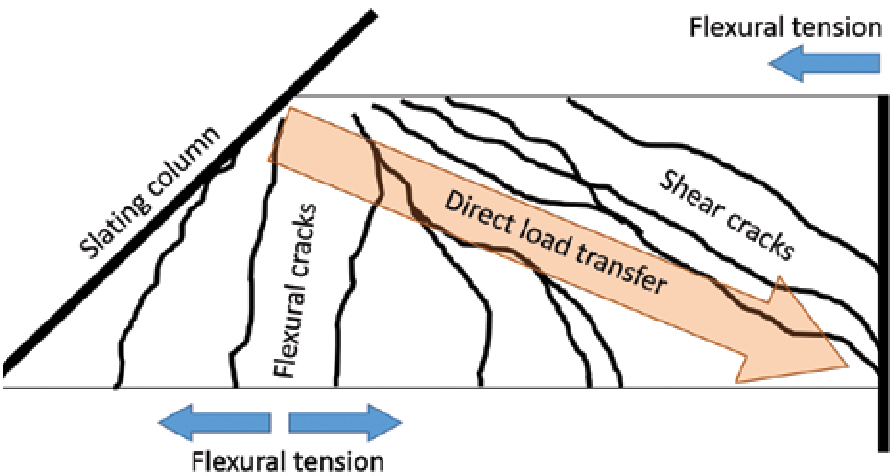


Figure 12. Assumed mechanism of direct load transfer from slating column to tower column in the short perimeter girders (Source: Daewoo E&C)

The directions of the diaphragm actions can be roughly divided into two directions – horizontal and vertical directions and the respective influencing area of each diaphragm action varies from Levels 11 to 20 depending on the location of slanting column in each level. As a result, the horizontal diaphragm action caused the cracks in the floor slabs where the perimeter girders and beams are oriented in horizontal direction. The vertical diaphragm action mainly caused the cracks in the beams oriented in vertical direction as shown in Figure 13. The vertical diaphragm action did not cause the cracks in the floor slab because the action was mostly resisted by the floor beams oriented in this direction.

The diaphragm actions were sufficient to cause cracks on the side of girders/beams but not enough to cause cracks under the bottom of girders/beams where most of longitudinal reinforcing bars are located. This is the reason why the cracks are observed only on the side of girders/beams.

Finally, the behavior of perimeter girders bounded by STCs and TCs might also have affected the cracks in other members. As mentioned earlier, the diaphragm actions in each level is caused by the STCs. After the structural resistance of the perimeter girders under STCs are degraded due to flexural and shear cracks, the loads covered by this perimeter girder must have been redistributed to other levels, and consequently have accelerated the diaphragm actions in the corresponding levels.

Methods of Reinforcement and Repair

Based on the investigation of cracks occurred in the structure of the Tower and analyzed causes of cracks, suggestions for repair methods of the cracks are given accordingly. The research team of the General Contractor mainly investigated the cracks and provided a report which served as a technical guideline. More concrete and detailed repair methods were given by the Structural Consultant to the repair subcontractor for proper retrofit and rehabilitation of the Tower. In the meantime, temporary supports had been installed under the perimeter girders with severe shear cracks against possible local failure of the girders (see Figure 14) and the development of cracks had been monitored constantly until proper repair methods were established and carried out.

Perimeter Girders Under Slanting Column and Dummy Column Location

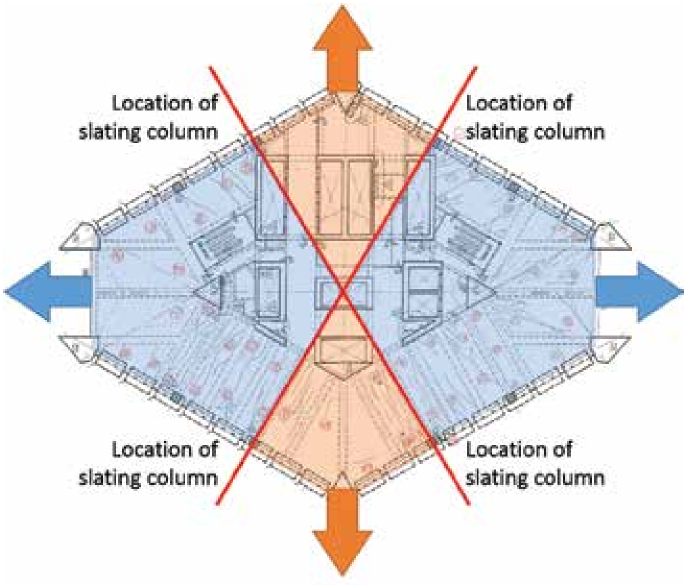
Considering the severe crack development in the girders at Level 16, these girders are judged to be best repaired by the method of section enlargement to compensate the insufficient contribution by the concrete. For other girders that are not severely damaged, repairing their flexural and shear capacity with carbon fibers might be sufficient. Actual retrofit was performed with steel members which provide sufficient strength to the cracked girders as shown in Figure 15. This was possible because the breadths of STC and TC are much greater than that of perimeter girder. The total number of perimeter girders reinforced with steel members was 12 at Levels 16, 25 and 34 excluding 4 girders at Level 48, which showed no sign of severe crack.

Floor Slabs, Other Perimeter Girders and Beams

Usual repair methods such as epoxy injection (see Figures 4 and 6) for cracks which have been already repaired with this method (or grouting) seem sufficient for these cracks. However, more detailed investigation of the diaphragm action during construction was recommended prior to the actual repair job, since a preliminary study on this subject has found that the cracks in these members might be closed due to in-plane compression as the construction proceeds toward its completion.

Conclusions

Structural cracks have occurred in the perimeter girders, floor slabs and beams during the construction of an irregular tall building. A collaborative investigation of cracks by the site and research teams of the General Contractor has found that the cracks have occurred due to the misassumption in the structural design by the Consultant, not due to the construction itself. This understanding has been shared between the General Contractor and the Consultant and proper corrective measures for repairing the damaged members were taken on time without interrupting the scheduled construction work.



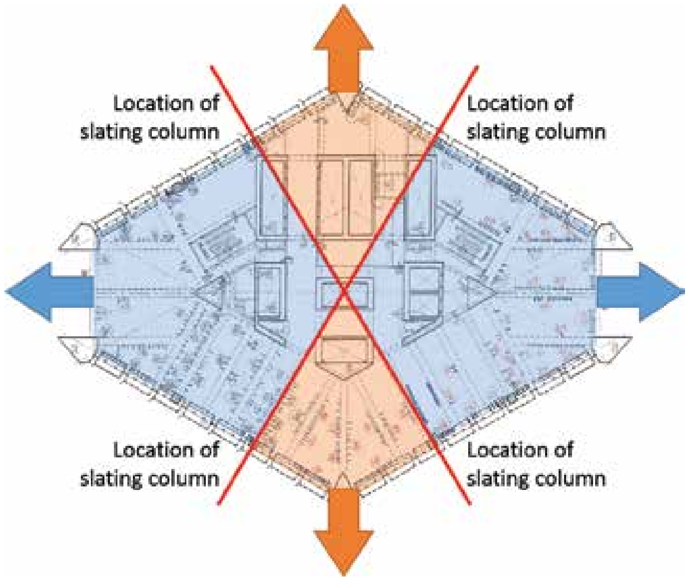


Figure 13 Crack patterns and in-plane tension caused by overall building behavior: for floor slab (above) and for girders and beams (below) (Source: Daewoo E&C)

Figure 14. Temporary installation of support under perimeter girder (Source: Daewoo E&C)

Figure 15. Cracked perimeter girder reinforced with steel member (Source: Daewoo E&C)

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