ASSESSMENT OF RC BUILDING STRUCTURES UNDER CONSTRUCTION SUBJECTED TO THE SUDDEN FAILURE OF SHORING ELEMENTS

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ABSTRACT

A significant number of structural failures have been reported during construction in recent years leading in some cases to the progressive collapse of the whole structure. The collapse often starts with the local failure of a single element. Although this is a well-recognized problem, studies on the effects of local failure in the shoring elements on the integrity of the shoring-structure system have not been carried out in the past. In this work advanced numerical finite element models were carried out of a three-storey RC building and its shoring system. Four scenarios of local failure were considered: sudden removal of a (1) shore, (2) joist and (3) complete shore line; and (4) incorrect selection of shores. The results indicated that the structure-shoring system was able to develop alternative load paths without dynamic amplification effects due to the large stiffness and redundancy of the system. It was also found that the integrity of the structure was not an issue in all cases studied although in severe scenarios (3 and 4) progressive collapse of the shoring system occurred leading to significant damage in the concrete slabs.

KEYWORDS. Alternative load path; Buildings; Dynamic amplification factor; Finite element analysis; Progressive collapse; Shore failure.

INTRODUCTION

Building reinforced concrete (RC) structures involves the use of temporary shoring or propping systems to support the slabs until the concrete is strong enough to support itself. Although there are many types of such systems, the one most commonly used is the shoring of successive floors (Adam et al. 2017; Buitrago et al. 2017, 2018b), in which the shores distribute the weight of the newly poured slabs among the lower floors. The main components of this system are: shores, joists and formwork boards. Recovering shores from the lowest level enables the construction of a new upper floor without the need for additional shores. The most basic option of this system consists of the shoring/striking (SS) of individual floors when the slab is able to support its own weight plus the loads transmitted to it from above. In order to reduce the costs of this system even further, two other alternatives have been suggested that include an intermediate operation on each floor: clearing or partial striking (C) and re-shoring or back propping (R).

The design philosophy of temporary structures differs significantly from permanent structures; in the former, the members are highly stressed during short period of time and they can be reused several times. Some of the latest simplified calculation methods that can be used to design these systems include those by Duan & Chen (1995), Fang et al (2001), Calderón et al (2011) and Buitrago et al (2016a; c). There are commercial pressures to shorten construction cycles to reduce costs which introduce demand on simplicity of the connections and components. Stability has been traditionally identified as one of the main reasons for concern and codes for design (e.g. BS 5975:2008+A1:2011) generally provide information to ensure sufficient bracing and lateral stability. Design guidelines for temporary works are now starting to introduce clauses to avoid progressive collapse with the idea that local failure of the temporary structures does not lead to failure of the whole structure (BS 5975 2011). This is a shift from traditional views in design practice where local failures in construction works were generally assumed to have negligible consequences compared to permanent works.

This variable tendency in design reflects that the risk of local failure of shoring systems (including its probability and consequences) is still not well understood. Due to the temporary nature of shoring systems the probability of local failure is higher and the consequences are lower compared to permanent structures. However, it is not well defined to what extent this is critical due to the lack of solid research in this area. According to a recent study by Buitrago et al (2018c), shore failure is the principal cause of the collapse of buildings under construction and have caused loss of human lives, injuries and material losses. Such failures are mainly due to: loads higher than allowable design loads on the shores, improper shore installation or lack of shore bracing. In addition, other studies on building failures under construction (Buitrago et al. 2018c; Carper 1987; Eldukair & Ayyub 1991; Hadipriono & Wang 1987; Kaminetzky 1976; Soane 2016) have shown that failure can also be due to inadequate design of the structure itself (i.e. insufficient anchorage length of reinforcement bars, insufficient reinforcement for flexure and punching shear or deficient detailing).

The numerical analyses of a RC building structure carried out in this work provide unique and novel evidence on the structural consequences of the structure-shoring system after the local failure of different shoring elements using the concept of notional member removal. This approach is commonly used for robustness analysis of permanent structures in research (Bao et al. 2008; Brunesi et al. 2015; El-Tawil et al. 2014; Fascetti et al. 2015; Olmati et al. 2017; Pham et al. 2016; Qian & Li 2013; Ren et al. 2016; Yi et al. 2011) and international codes (DoD 2009; EN 1992-1-1 2004; GSA 2000). Advanced dynamic analysis are unlikely to be carried out in design of shoring systems. Therefore, simplified approaches using Dynamic Amplification Factors (DAF) will be needed for design. This work shows that the DAFs used for permanent structures are not directly applicable to structure-shoring systems.

After the Introduction, Section 2 describes the building structure considered in the study including loading and construction considerations for the design of the shoring system. Section 3 describes the finite element (FE) model used to assess the local failure scenarios and Section 4 presents the results for each scenario. Section 5 contains the main conclusions drawn from the work.

DESCRIPTION OF THE BUILDING STRUCTURE

The study in this work focused on a three-storey flat-slab RC building in which shoring was used to support the slabs and formwork. This section describes both the building structure and the shoring. The weight of the fresh concrete poured into the top formwork was uniformly distributed among the previously built slabs and the ground by means of the shores as shown in Fig. 1.

Building structure

The building structure considered in this study corresponds to a real office building whose characteristics (geometry, reinforcement, materials) are thoroughly described in CS (Concrete Society 2007) and which was designed in accordance to Eurocode 2 (EN 1992-1-1 2004). The building had three floors with RC flat-slabs 300 mm thick, 3.5 m between floors and columns 400 mm square which were irregularly distributed in plan. A more exhaustive description of the building, which was also the subject of other studies, can be found in Olmati et al (2017). Fig. 1 shows a 3D view of the building.

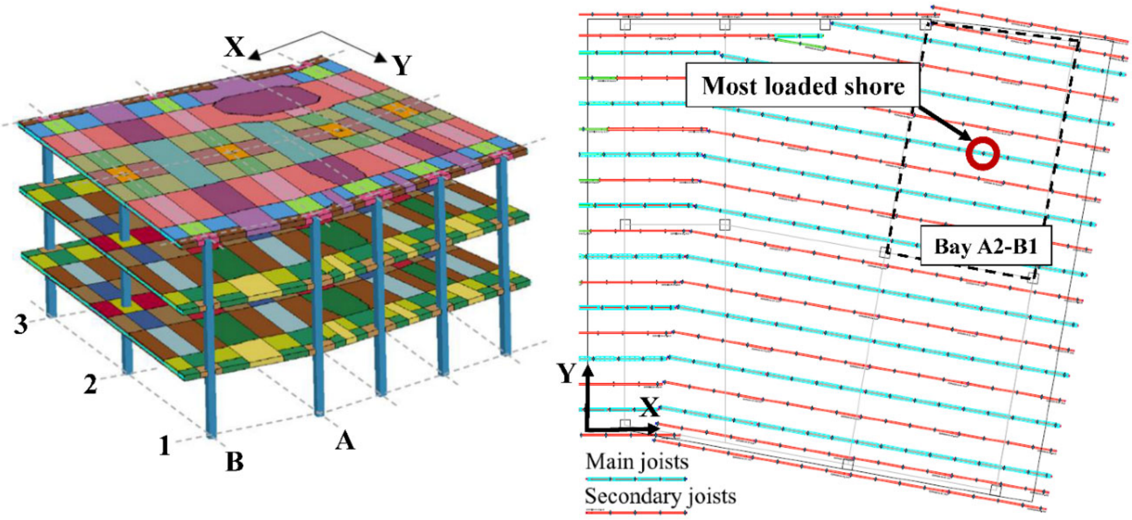

Fig. 1. Building geometry and sketch of the shoring system.

<u>Design of shoring system and loading during construction</u>

Permanent and live loads magnitude is an important issue to design properly a shoring system (Buitrago et al. 2018b). In the present study, the construction live loads in Eurocode 1 were adopted for consistency with the design of the building structure (made with the Eurocode 2). The weight of the structure and shoring were considered to be as permanent loads. Load safety factors for persistent and transient situations were 1.35 and 1.50 for permanent and live loads respectively (EN 1990 2002).

Calderón et al's simplified method (2011) and improvements suggested by Buitrago et al (2016a; c) were used to estimate the loads transmitted between the slabs and shores to design the shoring system. This approach has been shown to give better predictions than any other method available. An optimisation design approach was then followed using Buitrago et al's criterion (2016b) to check the construction process. In this work the SCS construction process (Shoring/Clearing/Striking) was adopted consisting of three successively shored floors (two cleared and one totally shored) and clearing of 50% of the shores (belonging to the secondary joists, as seen in Fig. 1). A standard spacing between joists and between shores was adopted which was equal to 1 m (2 m between joists on the cleared floors) and a new slab was poured every 7 days. This construction sequence was adopted following standard current construction practice (Adam et al. 2017; Buitrago et al. 2018b). Such cases generally result in high axial loads in the shores which is a highly unfavourable situation to look at notional member removal or local failure of the shoring elements. The maximum axial loads are carried by the shores connected to the foundation/ground during the pouring of the top floor slab connected by shores to the foundations (Alvarado et al. 2010; Buitrago et al. 2016c). The different structural failure scenarios analysed in sections 3 and 4 are defined for this most unfavourable construction phase.

For the building investigated, the maximum axial load on the shores developed after the pouring of the third floor slab when the first and second floor slabs were 14 days and 7 days old respectively. The position of the most heavily loaded shore in Bay A2-B1 is shown in Fig. 1. The maximum axial load was 47.6 kN which was estimated using the refined approach proposed by Buitrago et al (2016a) based on the proposal by Calderón et al (2011). A standard shore of 47.7 kN strength was finally adopted using the design catalogue ("Alsina Formwork Solutions" 2018) from a leading international formwork company. It was also verified that all the slabs could carry the loads during all the construction phases. A plan view of the shoring system is shown in Fig. 1.

DESCRIPTION OF THE FINITE ELEMENT MODEL

A nonlinear dynamic finite element analysis was carried out in this work using LS-DYNA software (LSTC 2012) with an explicit algorithm in the time domain to solve the equations of motion considering material and geometrical non-linearities. The FE model included the RC flat slab structure, shores and joists during construction. The analysis focused on the most unfavourable construction phase with the highest loads on the shores corresponding to the pouring of slab number three using SCS with two cleared floors and one fully shored as shown in Fig. 2. The FE model of the RC structure had been previously validated by Olmati et al (2017) and widely studied by Buitrago et al (2018d). In these two studies can be found a more in depth description of the simulation carried out.

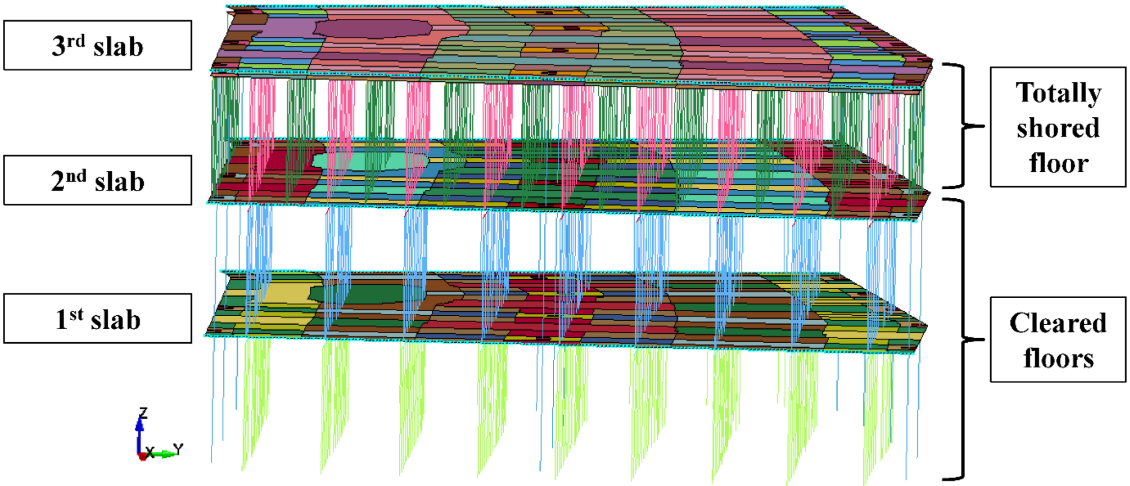

Fig. 2. Modelling of the structure.

The dead load (DL) was applied in the FE model as the self-weight of the different elements. The live load (LL) was also applied as a uniformly distributed mass on the slab. A characteristic value of the live load equal to 1.0kN/m^2 due to personnel was adopted (EN 1991-1-6:2005(EN 1991-1-6 2005)), since the self-weight of the shoring system is automatically taken into account by the FE model. The frequent load combination was used in the analysis (i.e. DL+0.5LL) corresponding to accidental load combinations in accordance with Eurocode (EN 1990 2002) and most international codes using the alternative load path method. In the FE analyses, the gravity acceleration was introduced gradually over time using a ramp function within t=0s and t=0.8s, similarly to Olmati et al (2017). This was followed by a time interval of stabilization and the introduction of a sudden local failure scenarios as described in Section 4.

LOCAL FAILURE SCENARIOS AND RESULTS

This section defines the different local failure scenarios of some of the shoring components to study their effects on the behaviour of the structure-shoring system. This is relevant since according to a recent study by Buitrago et al (2018c), shore failure is the principal cause of the collapse of buildings under construction.

The local failure scenarios considered followed the conventional notional member removal approach used traditionally for permanent structures. The aim of this study was to determine the effects of sudden failure of one or more ground-floor shores, which carry the highest loads when the third floor is poured, with two cleared floors and one fully shored. In this work, the local damage and the study on the behaviour of the shore-structure system focuses on a representative bay (A2-B1) as shown in Fig. 3. Four different local failure scenarios of the most heavily loaded shores were considered in A2-B1: 1) failure of the most heavily loaded shore (see Fig. 3b), 2) failure of the joist over this shore (see Fig. 3c), 3) failure of the complete shore line including this shore (see Fig. 3d) and 4) incorrect selection of shores. The following subsections briefly give the results obtained for the most aggressive scenarios (3 and 4). Results for scenarios 1 and 2, and detailed results for scenarios 3 and 4 can be found in Buitrago et al (2018d).

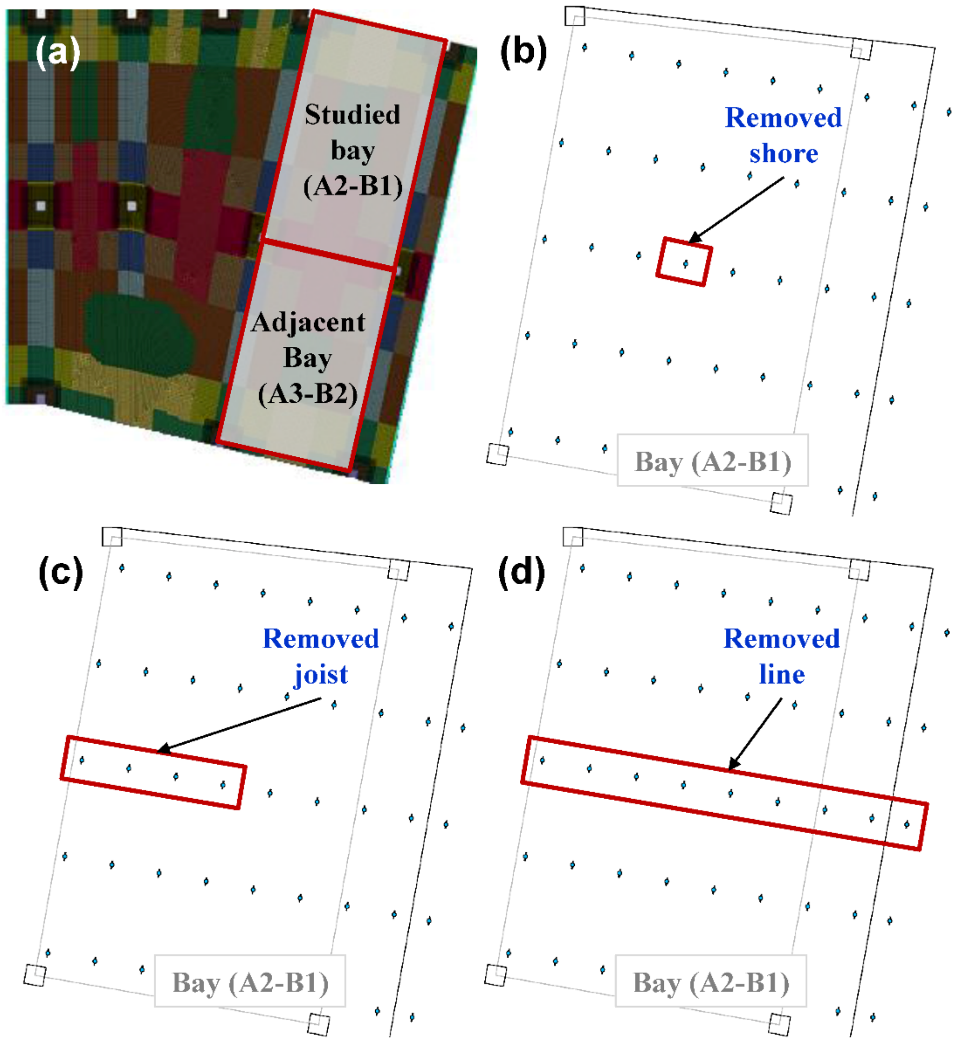

Fig. 3. Position of the bay under study (a) and scenarios 1, 2 and 3 of sudden failure of ground-floor shores (b, c and d).

3rd Scenario: failure of the complete shore line on the most loaded shore

Fig. 4 shows the sudden failure (at t=1.1 s) of a complete shore line (see Fig. 3d) causing the progressive collapse of all the other shores. As can be seen from the sequence of images in Fig. 4 (at 0.1s intervals), when the central line of shores under slab 1 is removed there is a chain reaction in all the shores at this level in which all collapse. In each step of the sequences in Fig. 4, the shores that fail in the following step (i.e. ultimate strength is reached) are shown in red. In this case, when a large number of shores fail between t=1.1 s and t=1.2 s the shoring under slab 1 becomes more flexible, increasing the deformation of this slab and the loads on the remaining shores around those that have previously failed. This increase in deformations can result in the shores under slab 1 reaching their ultimate strength (47.7 kN) and cause them to collapse one after the other. The deformation of the structure before and after the sudden event is shown in Fig. 5 for t=1.0s (Fig. 5a) and t=1.5s (Fig. 5b).

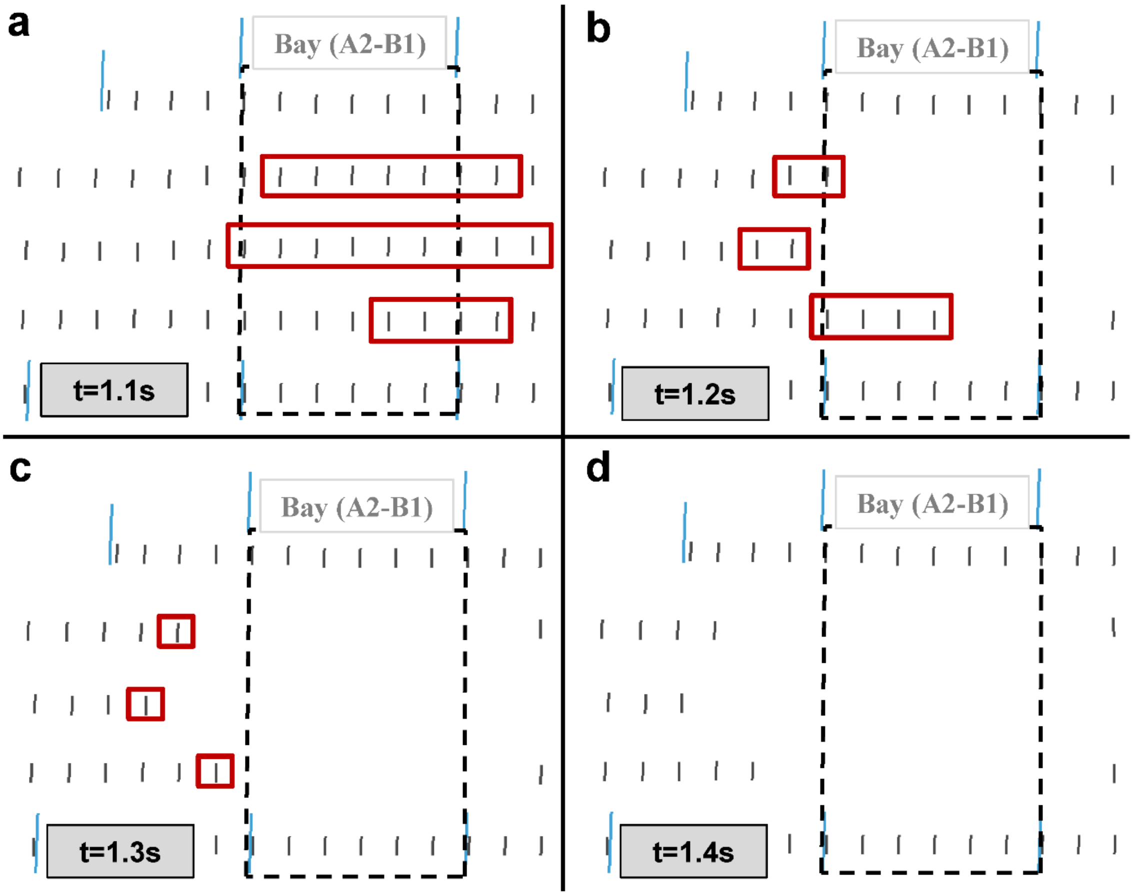

Fig. 4. Progressive collapse of the shoring system in the 3rd scenario.

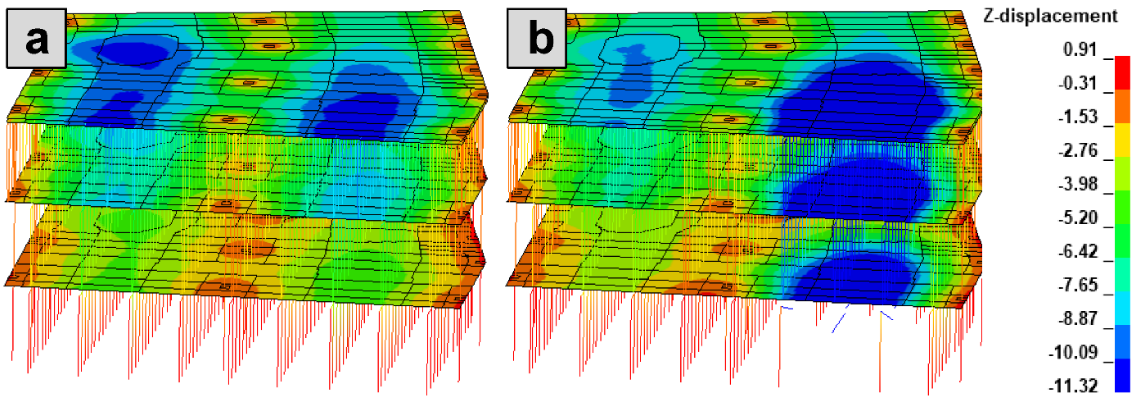

Fig. 5. Structure before (a) and after (b) the sudden event (units in mm).

Fig. 6 gives the moments obtained from the FE model in the bay under study (A2-B1) on the most unfavourable axis (bending moment Mx along the long span). Both the positive and negative moments in both slabs (see Fig. 6b and Fig. 6d) are higher than before the extreme event (Fig. 6a and Fig. 6c). Fig. 6 shows that the development of cracking at the position of the shore failures (See Fig. 3d) and in the zone close to the columns is severe (the cracking moment is 51.6kN·m/m and 45.3kN·m/m for the first and second slab respectively). The moments along the short span (not shown) also caused severe cracking in the slabs around the columns. Regardless of the damage predicted, the slabs complied with the flexure and punching requirements specified in Eurocode 2 (EN 1992-1-1 2004) for the accidental load combination considered.

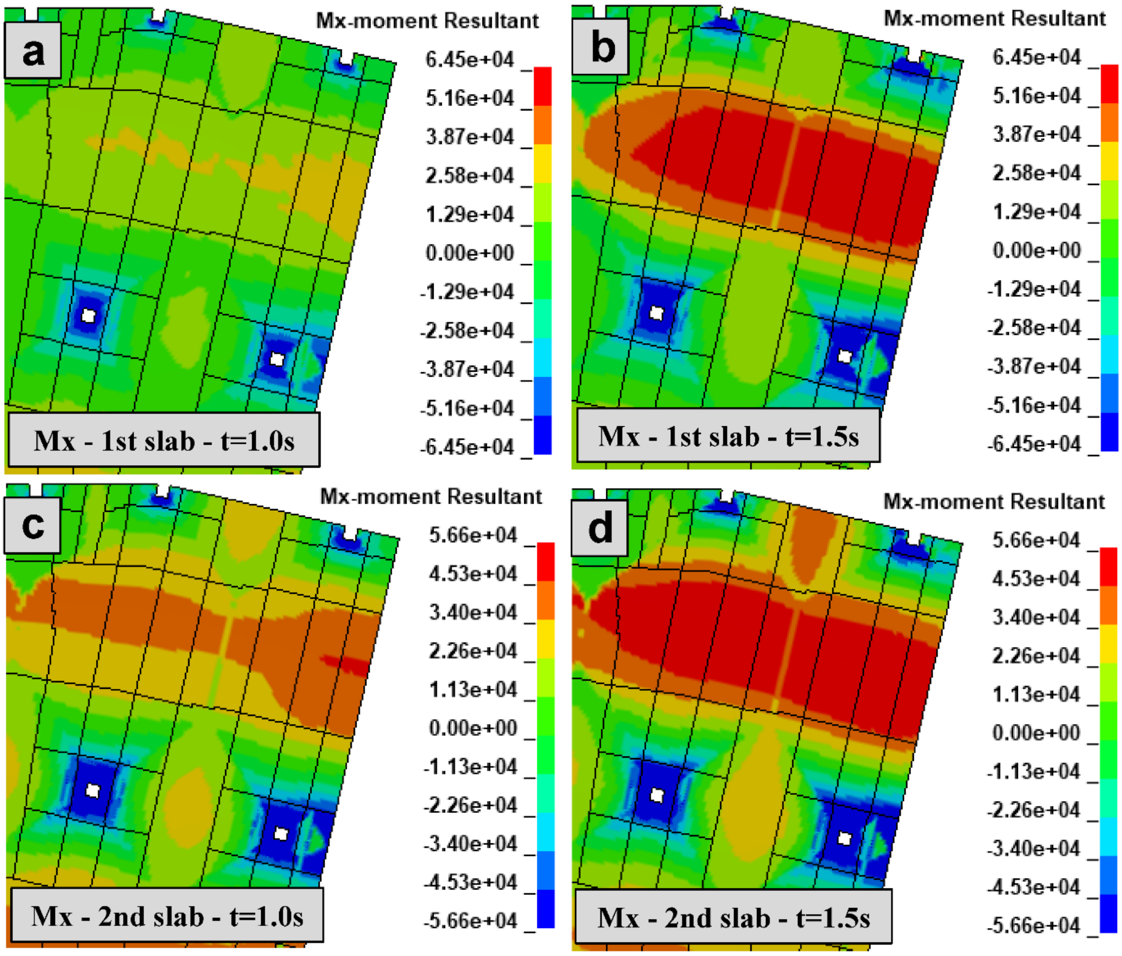

Fig. 6. Bending moments of first (a and b) and second (c and d) slabs before (a and c) and after (b and d) the accidental event in the third scenario (units in N·m/m).

It can be concluded that whilst the local damaged considered resulted in the progressive collapse of the shoring system, the building structure did not fail due to the efficient alternative load paths that could be activated in the shoring-structure system after local failure (i.e. load sharing between slabs 1 and 2 was critical, as seen from their displacements and loads). After the event the slabs carried higher loads although no dynamic amplification of loads nor deflections was observed from the FE analysis. The high level of slab cracking obtained in this scenario could result in potential serviceability and durability issues. In such cases the safety of the structure would need to be assessed in parallel with a cost analysis in order to determine possible repairing measures and whether it should be demolished.

4th Scenario: incorrect selection of shores

In design, incorrect sizing of the shores can occur due to a number of reasons. In this scenario a shore immediately below the strength of those used in the other scenarios was used from the same formwork provider ("Alsina Formwork Solutions" 2018). The ultimate strength of this shore was 30.6kN, well below the strength required of 47.6kN in design. After changing the mechanical characteristics (cross-section and shore ultimate strength) in the numerical model to those of the new shore, Fig. 7 shows how the progressive application of the entire expected load (i.e. quasi-static loading) between t=0 s and t=0.8 s caused the progressive collapse of the shoring system at t=0.66 s.

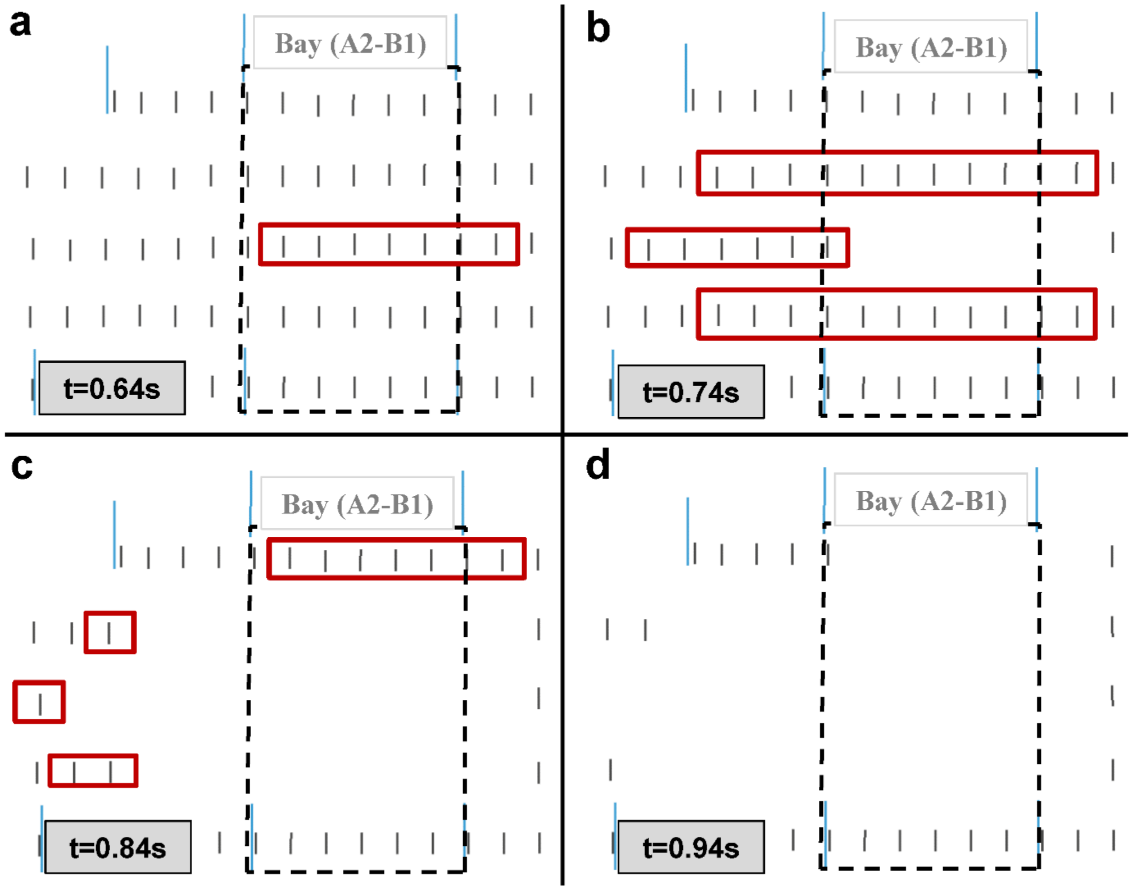

Fig. 7. Progressive collapse of the shoring system in the fourth scenario.

As can be seen in the images at 0.1s intervals (Fig. 7), after the start of the collapse all the shores under slab 1 begin to collapse one after the other, affecting the bay under study and an adjacent one. The shores remaining at the end of the sequence shown in Fig. 7 experienced loads below their ultimate strength. In Fig. 7 the shores under slab 1 shown in red failed due to excessive loading in the following time step. As in the third scenario (Section 4.1), as a large number of shores failed between t=0.64 s and t=0.74 s, the shoring under slab 1 becomes more flexible, resulting in a larger deformation of slab 1 and an increase of the load carried by the remaining shores adjacent to those that have previously failed. This increased load can then reach the ultimate strength of 30.6kN in some of the remaining shores and cause their progressive collapse. Fig. 8 shows the deformations of the structure-shoring system after the extreme event at t=1.5 s.

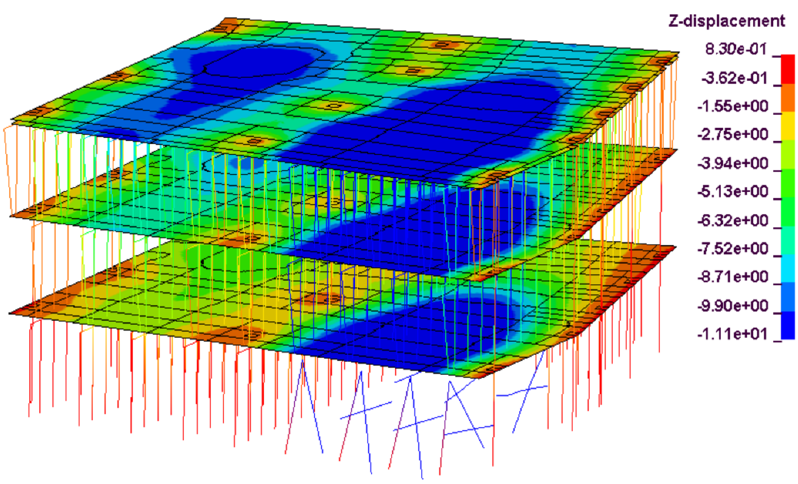

Fig. 8. Structure after the accidental event (units in mm).

Fig. 9 gives the bending moments in both directions obtained from the FE model in the bay under study. Both the positive and negative moments of both slabs exceed the crack moments (51.6 kN·m/m and 45.3 kN·m/m for the first and second slab, respectively) on a large part of the slab surface in the bay under study. Even under these high loads, the slabs comply with the ultimate strength flexure and punching requirements specified in Eurocode 2 (EN 1992-1-1 2004) for the accidental load combination considered.

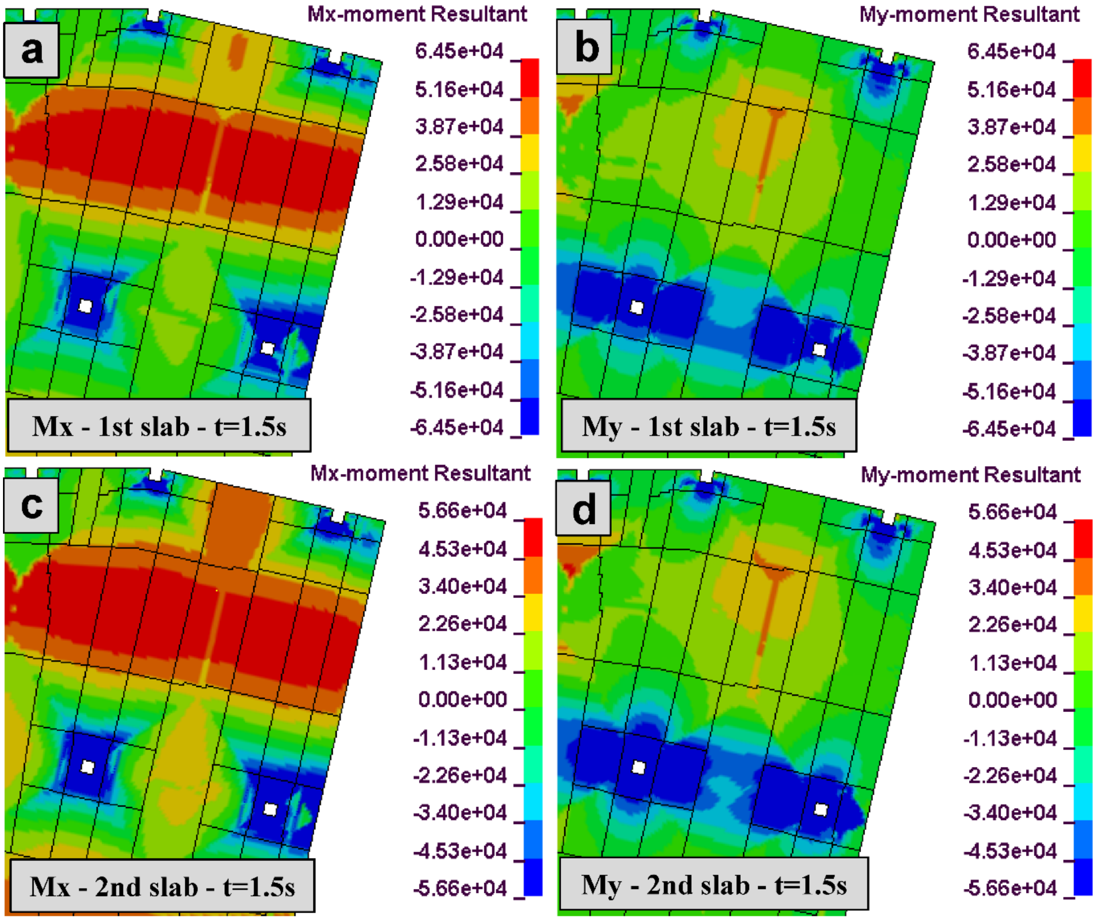

Fig. 9. Bending moments of first (a and b) and second (c and d) slabs after the accidental event for the fourth scenario (units in N·m/m).

Whilst this scenario resulted in significant damage, the structure did not collapse due to its ability to seek suitable alternative load paths, for which the load-sharing between slabs 1 and 2 is again critical. Even though the slabs carried significantly higher loads due to the event, and the deformability of the slabs was higher than in previous scenarios, dynamic effects (i.e. loads and deflections) were not generally observed in the analysis. Cracking of the slabs does increase after the extreme event, thus seriously affecting its serviceability limit state performance and durability. Similar to previous damaged scenario, in such situations it becomes necessary to assess the structural safety of the building to determine possible repairs and whether it should be demolished.

CONCLUSIONS

It has been shown that with correctly designed shoring an extreme event or local failure of some of its components does not necessarily lead to the progressive collapse of the entire structure. Although there is a higher likelihood of local failure during construction compared to the serviceability stage (i.e. column loss), the consequences of these failures can be lower in terms of cost and materials (generally the loss of human lives is limited). In the cases investigated with most serious consequences, it would be necessary to inspect the damage and assess the safety of the structure to decide whether it can be repaired or needs demolition.

It can be concluded that since the consequences of an event such as the loss of the most heavily loaded shore are rather small, it seems unnecessary to include explicitly such events in the design phase. Nor is it necessary to consider the failure of multiple shores since this probability is even smaller. It is important to note that the integrity of the building is assured in such cases only assuming that both the structural design and the shoring system provided are sound. It is advisable to take into account: a) the construction process when designing building structures, b) accurate and validated simplified calculation methods should be used to correctly estimate the loads transmitted between slabs and shores during building work (Adam et al. 2017; Buitrago et al. 2018b), and c) it is also important to use the correct RC construction procedures to avoid stability issues during temporary support situations. Even so, there is still room for the application of mitigation techniques to reduce the risk, for example by using load limiters on shores (Buitrago et al. 2015, 2017, 2018a; c). These measures could contribute significantly towards reducing the high-risk of progressive collapse observed in some cases during construction.

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