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Abstract
Reinforced concrete flat slab structures are widespread all over the world and present a high inherent risk. Designing flat slabs for a sudden column failure scenario ensures structures having a standard and sufficient level of robustness. However, buildings subjected to this hazard exhibit a complex behaviour and require cumbersome analysis to calculate their structural response. Alternatively, an approximate method, based on energy balance, is available. This method simplifies the dynamic analysis and reduces it to a static problem. In this direction, a new analytical approach to calculate the static response of slabs, based on kinematics and equilibrium, is currently being developed by the authors. By combining both methods, a straightforward procedure to provide flat slab structures with a homogeneous and measurable level of robustness is obtained. The numerical outcome will be compared with experimental results in order to refine and assess the accuracy of these approaches.

1 Introduction
Uncommon loads such as deliberate explosions and large impacts are not considered in a regular structural design. Structural robustness is referred as the ability of a system to resist these and other unforeseen actions without suffering disproportionate damage. Collapse cases like Ronan Point, London 1968, Alfred Murrah Building, Oklahoma 1995 and World Trade Center, New York 2001 have underlined the necessity of increasing the robustness of structures. However, preventing damage in buildings against any possible hazard is practically and economically unfeasible. Therefore, most efforts are currently focused on establishing standardized methods for providing building structures with an adequate, homogenous and measurable level of robustness.

Different strategies for increasing robustness by design have been developed during the last decades. Design codes [1, 2] focus on the alternative load path approach, which consists in increasing continuity and structural redundancy in the structure to allow redistribution of loads and limit the damage in the structure in case of local failure. Most guidelines use a hazard-independent notional column removal as a standard local failure. The level of structural integrity is based on the building’s performance for this failure mode. The extent of damage in robust structures must not exceed prescribed limits, which vary between different design codes. These standards, however, do not establish an approach that accounts for the impact of falling debris from such accepted damage. Moreover, they do not consider the fact that such damage in buildings with regular layouts will spread to all floors above the lost element. A further considerable shortcoming is that most of these codes do not give specific guidance on how the structural analysis for this hazard scenario should be performed. In this direction, assuming an instantaneous column failure as a design scenario allows to standardize and determine an upper bound of the dynamic component of the phenomenon.

2 Uncertainties on the robustness assessment of flat slab structures
Designing flat slab structures for a sudden column failure scenario provides buildings a standardized and sufficient level of robustness. Hence, most international codes suggest or require buildings to be designed or evaluated for this event. A measurable and homogeneous procedure to assess structural robustness is to estimate the maximum load-carrying capacity of the building after a sudden column failure without exceeding the prescribed damage limits and compare it to the design loads. This procedure is, however, relative complex and produces some issues for structural engineers:

- The structural level at which the flat slab structure must be analysed for a column removal and corresponding boundary conditions are not clear
- Linking robustness with damage makes the analysis full of uncertainties and subjectivities

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The main aim of the present investigation is to shed some light on these problems proposing different approaches, so that at the end a straightforward global procedure to provide flat slab structures with a homogeneous and measurable level of robustness is obtained.

3 Structural idealization of flat slab structures subjected to a column failure

Guidelines do not define at which structural level a building must be analysed for a column failure. When a column is suddenly removed, compressive forces in all supports above the target column disappear within a few milliseconds and are redistributed to the neighbouring columns. The dynamic gravity loads are transferred by the slabs of each connected floor above the lost element, which will all undergo identical vertical deflections. Buildings with a regular layout, where all floors are of similar strength and stiffness and bear equal gravity loads, will all stand or will all collapse. Therefore, for most common building structures, the structural analysis model can be reduced to a single floor, neglecting the vertical interaction.

Collapse will take place if the resistance of the horizontal elements is not sufficient or if the supports fail due to the supplementary compression forces. However, columns generally are capable to accommodate this increase and consequently only the behaviour of the slabs and their connection with the supports are relevant for the collapse resistance of buildings.

Flat slab floors subjected to uniform vertical loading normally present two types of collapse pattern, one involving general folding of the slabs (Fig. 1 (a)) and the other involving local slab collapse around the columns (Fig.1 (b)) [3]. However, if a column is removed, bending moments in the slabs bridging over the remove column are strongly increased by the double-span effect and the dynamic component. Thus, the collapse pattern changes, and all the damage is concentrated in the directly affected bay by the column removal (Fig. 1 (c)). This collapse mechanism is similar to the yield-line pattern of an isolated slab with continuous vertical support along the edges. Hence, the structural analysis model can be further reduced to the directly affected bay with specific boundary conditions.

These boundary conditions should produce similar effects on the slab as the surrounding structure and therefore vary depending on the situation of the slab within the floor. Lateral restraints have a significant relevance on robustness assessments as they allow slabs to develop membrane forces that enhance their load-bearing capacity. The available lateral stiffness has to be examined always very closely because compressive membrane action relies on the restriction of very small horizontal translations and large horizontal forces are involved. In this direction, an investigation of the enhancement of the load-carrying capacity of typical fully clamped slabs due to compressive membrane forces has been performed by the authors. The analysis is based on the approach described by Keenan [4]. The outcome of this study, together with the most important details of the analysis, are displayed in Fig. 2.

It can be observed that the enhancement of resistance decreases for both, increasing horizontal translations ($s$) and span-thickness ratios ($L/t$) of the slab. The span-thickness ratio of flat slabs lies normally in the range 20-30. After a column removal, this ratio increases to values from 40 to 60. The horizontal translations of the edges $s$ are expressed in terms of the span $L$ of the slab. Assuming a span length of 12 m after the support loss, a value of $s = 0.0003$ represents a total horizontal translation of 3.6 mm or 1.8 mm from each side. It is reasonable to expect that, even in buildings with large lateral stiffness, such small movements will occur during the structural response. The enhancement due to membrane compressive forces is therefore negligible for column removal scenarios.
4 Robustness of flat slab structures for sudden column failure scenarios

It has been previously pointed, that an effective procedure to assess the structural robustness of a flat slab structure is to estimate the maximum load-carrying capacity of the building after a sudden column failure without exceeding the prescribed damage limits and compare it to the design loads. Besides, it has been demonstrated that the structural analysis of these buildings subjected to a column failure can be reduced to the analysis of the isolated directly affected bay. If damage is assumed and this isolated slab fails by not being able to reach equilibrium after a column removal, the previous simplification is, however, not valid. Most likely, progressive collapse will occur, spreading from the failed slab throughout the building until a new equilibrium position is reached. The robustness evaluation will then depend on a wide range of parameters, most of them unknown and difficult to estimate.

No failure of the directly affected bay by the column removal, however, results in no further progressive collapse of the building. The collapse resistance of the building is then directly linked to the capacity of this bay to redistribute the gravity loads. By imposing no failure of the directly affected bay for design and assessment, the robustness of the whole building can be related to the robustness of this bay, which can be analogously calculated by comparing its particular maximum dynamic load-carrying capacity to the design loads. Nonetheless, calculating this load-bearing capacity for an isolated slab is still highly complex, as it involves structural dynamics as well as material and geometrical nonlinearities due to the expected large strains and displacements [5].

5 Dynamic component simplification: the energy balance method

Nonlinear time history analyses require large expertise and are mostly too arduous to be applied in practice. On the other hand, static analyses with simplified dynamics effects are very popular among engineers, but they do not represent the structural behaviour in the inelastic range accurately.

Alternatively, a simplified method based on energy balance is available. This method was originally defined for blast resistant design by Newmark [6] and further adapted for sudden support removal scenarios by different authors [7, 8]. This approach leads to the approximate maximum dynamic response of the structure and simplifies the dynamic component, reducing the problem to estimating the static response of the structure. This method accounts for energy absorption capacity, ductility supply and redundancy [8], offering a compromise between accuracy and complexity.
Physically, this method can be explained in the following terms: immediately after the column is removed, the potential energy of the loads is suddenly released and equilibrium is not satisfied. Thus, the slab deflects in order to absorb more strain energy. The excess of external work is transformed into kinetic energy, increasing the velocity of the slab. As the structure deflects, the kinetic energy decreases, and so does the difference between the potential energy and the stored elastic and inelastic energy of the slab. When this difference and the kinetic energy are zero, the maximum dynamic response is reached. This approach can be graphically represented in terms of the static response of the structure as illustrated in Fig. 3 (a). The maximum dynamic response corresponds to the deflection, for which the area under the static response curve (strain energy) is equal to the rectangular area below the horizontal line of the suddenly applied gravity load (external work). Proceeding for different loading levels, a dynamic capacity curve can be obtained. Hence, the maximum dynamic load-bearing capacity of a slab for robustness assessments can be estimated by just calculating its static response without performing a dynamic analysis.

However, this method presents some implicit errors, leading to approximate results, as it is based on a set of assumptions which real structures do not completely fulfil:

- The effects of a sudden column loss are introduced in the analysis as a sudden application of the loads. Thus, all the work performed by these loads is considered to have a dynamic nature, while in reality a portion of this external work is static due to the original deflections before the column is suddenly removed.
- Real structures present an infinite number of deformation modes, which will be differently excited by the dynamic loads, reaching their peak response at different time moments. Hence, the kinetic energy of the whole system is not generally zero at the moment of the maximum response. Only for single degree of freedom systems this assumption is entirely valid.
- The energy dissipated by damping, before the peak response has been reached, is neglected.
- Strain rate effects are also neglected. The method considers that the strain energy stored by the structure for a giving displacement is the same for both, dynamic and static responses.

A comprehensive description of the method, together with an investigation of the implicit errors raised from the presented assumptions has been performed by the authors [9]. This study concludes that the application of this approach can yield to accurate results, as it can be seen in Fig. 3 (b). Besides, this study reveals that the energy balance method always underestimates the strength of the structure and leads to conservative results. Additionally, applying this approach, the uncertainties related to the dynamic component are significantly limited, as the dynamic analysis is normalized and the problem is reduced to calculate the static response of the structure. In this direction, the energy balance method is a promising approach to simplify robustness assessment and design of structures.

Fig. 3  a) Concept of the energy balance method; b) Application to a fully clamped beam [9]

### 6 Static response of laterally unrestrained slabs

The maximum dynamic load-bearing capacity of a slab is directly related to its static pushover response, specifically to its strain energy absorption capacity and ductility. The main aim for assessing robustness should therefore be to accurately estimate the accumulated strain energy of the slab for increasing deflections and define its ultimate load and deflection. Hence, most care must be taken in calculating the post-yielding behaviour of the slab, as most of the strain energy is absorbed at this phase.
A flat slab subjected to a column removal could present two basic failure modes: flexural failure and punching shear failure. The event of a column removal represents a severe change of the original structural scheme of a flat slab. Close to the remaining supports, the negative bending moments largely increase due to the double-span effect. Besides, the slab-column connection of the removed support has to bear huge positive bending moments it was not originally design for. Shear forces at the remaining columns are, however, just moderately enhanced by the redistribution of the original vertical reaction of the removed support. Based on this fact, the investigation of the authors has been focused on the flexural behaviour of laterally unrestrained slabs, disregarding punching shear failure.

Laterally unrestrained slabs will develop membrane action at relatively large deflections through the creation of a compression ring along the edges that internally balances the tensile zone originated in the centre of the slab (Fig. 4).

Continuous vertical support along the edges is required for this mechanism to be developed. However, the elastic deflections between columns are negligible in comparison to the large plastic deflections at the slab centre after a column removal. Hence, the flexural capacity of flat slabs can be estimated through a slab model with continuous vertical support along the edges and no lateral restraint.

Considering second order effects, the tensile forces in the slab centre monotonically enhance the flexural capacity of the slab for increasing deflections. This enhancement continues until the rotation capacity of the yield lines is exceeded, the compression ring fails or reinforcement rupture occurs at the internal ellipse, leading to a flexural collapse of the slab.

The analysis of all the described phenomena is rather complex and needs to be performed through advance models and numerical approaches like the finite element method. Alternatively, a new approach based on the kinematics of a perfect rigid-plastic slab and the equilibrium of the internal forces originating from the consistent deformations, is currently being developed by the authors. This method allows estimating the load-carrying capacity of laterally unrestrained slabs by means of three stages: a first elastic stage, a transitional elastic-plastic stage and a membrane action stage. In this approach, membrane forces are presented as a consequence of the kinematic compatibility of the slab once the edges start moving inwards. Besides, the development of an axial crack across the slab centre perpendicular to the longer side of the slab at large deflections, as observed in several experimental tests [10], has been incorporated in this method. The theoretical part of the method has been recently concluded and the authors are currently implementing this approach in MATLAB®. The next planned step is to refine and verify the accuracy and reliability of the method by comparison of the numerical outcome with results from different experimental campaigns of laterally unrestrained slabs.

The final objective would be that, using this approach for calculating the static load-bearing capacity of laterally unrestrained slabs together with the energy balance method, the maximum dynamic capacity of these slabs could be accurately estimated. Hence, straightforward, precise and homogeneous robustness assessments and design of flat slab structures could be performed.

7 Experimental research

In order to confirm the validity and accuracy of the described procedure to estimate the maximum dynamic capacity of a slab subjected to a sudden column failure, the authors plan to conduct an experimental campaign. The main motivation to carry out this campaign is the lack of experimental results of slabs subjected to a sudden support removal. In order to reduce the number of tests, only the general case for an interior support removal will be tested. These experiments will also offer the possibility of assessing the inherent protective capacity and robustness that regular design yields to slabs.
The prototype will basically consist of a floor slab with continuous vertical support along the edges that allow free horizontal displacements and present a removable support at the slab centre. The laterally unrestrained may be simulated by a pin connection at the bottom of the vertical support which can freely rotate at the floor level and therefore exhibit free horizontal displacements at the slab level.

The prototype slabs are intended to represent the characteristics and geometry of common flat slab structures. They will be therefore designed as conventional structures and will have a free span of approx. 6 m and a thickness of 225 mm. These prototypes will be reduced by a scale factor of approx. 1/2.5. This scale factor is not only compatible with the geometrical restrictions of the laboratory but also allows using standard materials and construction procedures and limits further scaling problems.

Static and dynamic tests will be performed on equal test models. The static test will consist on an experimental pushover analysis until failure using a displacement-controlled loading procedure. The dynamic tests will consist in statically loading the slabs for different load levels, proceeding afterwards to suddenly remove the mid-support so the dynamic component is introduced. The slabs will be instrumented so that the history of the strains and strain rates in concrete and reinforcement, the displacements along the supports, and the deflections and accelerations of the slabs can be determined.

Performing both static and dynamic tests on equal specimens will help isolating the dynamic effects and specially investigating their impact on the ultimate strength, membrane forces and damage level of the slabs. The outcome of the described tests will be used to assess the accuracy of the energy balance method by using both, experimental static pushover and time history dynamic response results. Furthermore, the accuracy of the previously described approach for calculating the static response of laterally unrestrained slabs will be evaluated by comparison with the experimental results.

References


