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Modelling of floor joists contribution to the lateral stiffness of RC buildings designed for gravity loads

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ABSTRACT

The work herein presented is aimed to the estimation of the contribution of floor joists acting as an "equivalent beam" in RC buildings designed for gravity loads where the deck has often no beams in the direction parallel to the warping of the floor joists. Regarding this issue a simplified theoretical model has been preliminarily developed. This model accounts for the ratio between the torsional stiffness of transverse beams supporting the floor joists and the flexural stiffness of the floor joists. The relation obtained has been applied to compute the number of collaborating joists defining the equivalent beam for a sample of single-story and multi-storey buildings with different geometrical characteristics. Successively, by means of a wide comparison between the lateral stiffness of a structural model based on the "equivalent beam" and the 3D structural model including all the joists, a correction factor is proposed to improve the accuracy of the formulation based on the simplified theoretical model.

1. Introduction

Reinforced Concrete (RC) buildings currently represent the highest percentage of the built heritage in many countries all over the world, especially in Italy, Greece, Turkey and other Mediterranean earthquake-prone countries. Most of these buildings were designed before the advent of seismic codes, being constructed in the fifties–seventies, showing peculiar structural characteristics and material qualities. They frequently have a framed structure constituted by beams and columns with masonry infilled walls along the perimeter and internal beams spanning in one direction only (Fig. 1). Therefore, in the other direction, frames are connected only by floor joists without linking beams in the direction parallel to the floor joists. Aiming to the vulnerability assessment and seismic retrofitting of existing buildings, there is the need, on one hand, to make available to designers accurate calculation models to predict the ultimate behaviour of reinforced concrete members accounting also for the applied strengthening technology [1–3] and, on the other hand, the need to properly evaluate the actual lateral stiffness and strength of the structure.

As it is well known, the knowledge of the overall lateral stiffness of the building structures is an essential issue in the determination of the dynamic properties of the structure. The lateral stiffness is mainly governed by the flexural stiffness of columns and beams, as it usually occurs in case of space frames. Conversely, in case of building structures without linking beams connecting moment frames supporting gravity loads, also the flexural stiffness of the floor joists is involved. In fact, the floor joists contribute to the lateral stiffness, interacting with the torsional stiffness of the supporting beams and thus restraining the rotation of the columns at the floor levels. Although RC buildings designed for gravity loads only have often exhibited unsatisfactory seismic behaviour, it is known that they have an inherent lateral resistance mainly due to the complete frames (frames with beams and columns). However, the contribution of joists in RC buildings without linking internal beams in the joists direction could be not negligible. In a sense, it is not correct to admit that the floor does not contribute at all to the lateral seismic resistance of the structure. In fact, as observed after recent past earthquakes (e.g. Irpinia 1980, Turkey 1999, L'Aquila 2009, Emilia 2013) RC buildings designed with outdated criteria have been able to support moderate seismic events by calling into account both the joists contribution and/or the infill walls contribution [4–6].

From a seismic point of view, it is of paramount importance to account for the joists collaboration. In fact, if their contribution were completely neglected, the structural model should be represented by simple cantilever columns connected by pinned rigid beams simulating the in plane stiffness of the deck, i.e. the diaphragm action. Such a model is characterized by the minimum lateral stiffness provided by the columns only. As a consequence, it should suffer very high lateral displacements for low values of the seismic intensity, and, as already underlined, this is not supported by the experience of past earthquakes.

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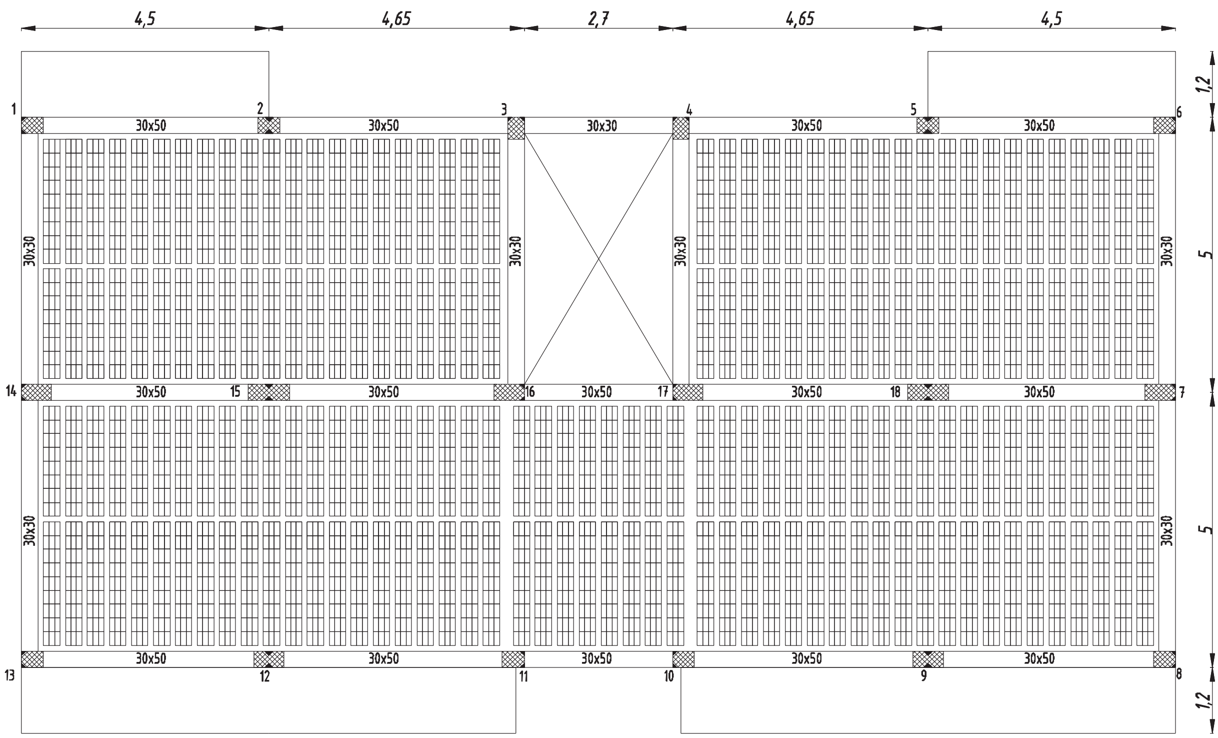

Fig. 1. Carpentry of a typical floor.

Many researchers analysed the seismic behaviour of existing RC buildings and their vulnerability under seismic actions [7–10], but a little part of them has focused the attention on the contribution of the floor structural system to the lateral stiffness and strength of the building structure. With reference to the constant thickness slab system, most design codes since '70s [11–13] permit the use of a limited width of slab stripes for evaluating the ultimate strength of a beam in the particular case of horizontal loads. Other researchers proposed alternative methods to the rules provided by codes for the evaluation of the floor slab contribution [14–17]. However such a kind of constructional system is widespread especially in U.S., Canada and Japan while the one-way joist system with asmolen infilled mainly refers to Mediterranean countries. Regarding this topic, European rules for existing structures [18] present an evident gap entrusting the designer to take into account or not the joist contribution to the overall behaviour of the structure. The point is how to take into account this contribution. In fact, on one hand, if the joist collaboration is not considered, in case of linking beams missing in the direction parallel to the floor joists, the frame behaviour would be missing and the columns would work with a cantilever scheme. On the other hand, it would be excessive to consider as collaborating all the floor joists included in a stripe on the column line whose width is equal to the bay span. Masi et al. [19,20] suggested, on the basis of the torsional and flexural stiffness of structural elements around the columns, a stripe of the tile lintel floor equal to about 1.0 m. However, this solution seems to be too simplistic, because it appears unlikely that, for different geometrical and mechanical structural characteristics, the collaborating stripe of the floor has always the same dimension.

For these reasons the primary aim of this work is to bridge the lack in European rules [18] by proposing a relationship to estimate the area moment of inertia of an "equivalent beam" representing the contribution of the floor joists to the frame behaviour.

In order to develop such relation a simplified theoretical model has been preliminarily analysed. It takes into account the influence of the ratio between the torsional stiffness of the supporting beams and the flexural stiffness of the floor joists. The relation thus obtained has been applied to a sample of single-storey structures with different geometrical characteristics. The same sample of structures has been analysed by means of a FEM single-storey three-dimensional model, including not only the beams and the columns but also the floor joists. The lateral stiffness resulting from the analysis of the 3D FEM-model including all the floor joist has been compared to the stiffness of the single-one obtained by means of the "equivalent beam" approach. In particular, a parametric analysis has been carried out by varying the size of beams and columns, the height of the floor and the span of the structural scheme. As a result, the sensitivity of the relationship, based on the simplified theoretical model, to the structural parameters involved, has been investigated. Finally, on the basis of the numerical analysis result the theoretical relation has been improved by means of a correcting factor. In order to further check its validity, the amended formulation has also been applied to derive the "equivalent beam" for modelling the floor joist behaviour in some multi-storey structures. The results obtained have been compared with those derived from a 3D FEM-model, including all the floor joists, pointing out the accuracy of the proposed formulation.

2. Theoretical model

In order to estimate the floor joist contribution to the building lateral stiffness an equivalent beam approach can be applied. This equivalent beam runs parallel to the direction of the floor joists. Regarding the translational behaviour, the floor deck can be assumed infinitely rigid in its own plan, so that it always constitutes a rigid link between the columns preventing relative horizontal displacements at the floor levels. Conversely, regarding rotational behaviour, two limit schemes can be identified. The first one assumes an infinite torsional deformability of the longitudinal beams so that the contribution of the floor joists to the rotational stiffness of the nodes located at the end of the columns, i.e. at