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Displacement based design for precast concrete frames with not-emulative connections

Andrea Belleri

Department of Engineering and Applied Sciences, University of Bergamo, Italy

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ABSTRACT

The Displacement Based Design (DBD) methodology for precast concrete frame structures with not-emulative connections is investigated herein. The seismic design procedure is applied to both single-storey and multi-storey structures. Industrial and office buildings, warehouses and commercial malls with a structural layout typical of the European market are considered: cantilever columns resting on isolated footings connected at the floor level to pre-stressed precast beams, supporting pre-stressed precast concrete floor or roof elements. The need to control the lateral seismic displacement is dictated by the high flexibility of these structures, which in turn is associated to the structural scheme and to the inter-storey height.

Starting from the general displacement based design procedure, the paper focuses on how properly taking into account the influence of column-to-foundation and beam-to-column precast connections; expressions and procedures are developed to determine the yield curvature, the equivalent viscous damping, the effective height and the effective mass of the single degree of freedom substitute structure adopted in the DBD procedure.

The proposed procedure is applied to selected case studies and validated through non-linear time history analyses, showing the ability of the design procedure in controlling lateral displacements.

1. Introduction

Precast concrete structures are widely adopted, especially in the industrial and commercial sector, due to the reduced on-site construction time and cost effectiveness, to the ability of covering wide spans with pre-stressed elements and to a better quality control of materials and structural elements compared to traditional reinforced concrete structures. Although different typologies of lateral force resisting system solutions are available in the literature and in the worldwide practice, such as reinforced concrete emulative structures [1,2], jointed ductile connections [3–5] and rocking and hybrid walls [6,7] among others, the majority of European industrial buildings, warehouses and commercial malls are single-storey or few-storey buildings with a simple structural layout: cantilever columns, connected at the floor and at the roof by simply supported precast and pre-stressed beams, supporting pre-stressed concrete elements. The columns are placed and grouted on-site in isolated precast cup-footings or connected to shallow foundations through mechanical splices or grouted sleeve solutions [8–11]. The column-to-beam connection is typically pinned [12–14] and the energy dissipation is provided by the development of plastic hinges at the base of the columns.

The hinged-frame static scheme and the high inter-storey height lead to flexible structures in which the contribution of elastic displacements is higher compared to traditional reinforced concrete frames. If not appropriately considered in the design phase, this high flexibility could lead to displacement incompatibility between structural elements [15,16] (the contact between the end of the beam and the column during their relative rotations may lead to a change in the boundary conditions) and between structural and non-structural elements, such as precast cladding panels, causing their premature failure [17–23]. The seismic performance of these structures is therefore related to inter-storey drift control rather than material strain limitations.

The seismic design approach commonly adopted by professional engineers, as in EN 1998-1 [24], is the well known force based design (FBD): the equivalent lateral inertia forces are obtained considering a system with reduced flexural stiffness (an effective modulus of inertia I_{eff} is defined as a percentage of the gross module I_g to account for concrete cracking) and an acceleration spectrum scaled by a force reduction factor depending on the structural typology is used. The lateral displacements are obtained at the end of the design process. For flexible structures, as those

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E-mail address: andrea.belleri@unibg.it

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considered herein, the displacements are obtained from the equal displacement approximation which states that the displacement ductility is equal to the force reduction factor.

Following the FBD procedure [25], the results could be affected by the aforementioned sources of approximations: the force reduction factor, the effective modulus of inertia and the equal displacement approximation. Although these limitations could be overcome by the definition of refined formulations, the displacements are evaluated at the end of the design process. Being lateral displacements so important in the seismic response of the structures considered herein, a more rational approach would consider the displacements as the input of the design process. Performance based design methodologies, such as displacement based design (DBD), follow this approach.

Starting from the DBD procedure proposed by Priestley et al. [26], the paper considers how to implement typical details of precast concrete structures, such as column-to-foundation and beam-to-column connections, in the design process. Regarding the column-to-foundation connections, the influence on the system energy dissipation capacity and on the yield curvature is investigated; the former affects the equivalent viscous damping formulation, while the latter affects the displacement ductility formulation. Regarding the beam-to-column connections, the paper analyzes the influence on the effective height and effective mass of the substitute structure used in the design process. Finally, the proposed procedure is applied to selected case studies, both single and multi-storey buildings, and validated by means of non linear time history analyses.

2. Displacement based design

The DBD procedure [26] adopts a substitute structure approach [27], which considers a single degree of freedom (SDOF) elastic structure with stiffness equal to the secant stiffness at maximum displacement and with damping equal to an equivalent viscous damping accounting for hysteretic energy dissipation.

The definition of the structural deflected shape (Δ_i) for a considered multi degrees of freedom (MDOF) system is the first step of the procedure. The deflected shape represents the first inelastic mode of vibration and it is associated to a particular structural typology. Priestley et al. [26] report the deflected shapes for typical structural typologies, based on analytical derivations or resulting from non-linear time history analyses. It is worth noting that the diaphragm stiffness could alter the lateral deflection, with greater lateral displacements in the central part of the diaphragm, especially when the lateral force resisting system is located at the diaphragm edges. The properties of the SDOF substitute structure, as the target displacement (Δ_d), the effective height (h_{eff}) and the effective mass (m_{eff}), are obtained directly from the MDOF-system target deflected shape, which is selected to limit, for instance, inter-storey drifts or material strains. Such properties are:

$$\Delta_d = \frac{\sum_{i=1}^{n} m_i \Delta_i^2}{\sum_{i=1}^{n} m_i \Delta_i} \tag{1}$$

$$h_{eff} = \frac{\sum_{i=1}^{n} m_i \Delta_i h_i}{\sum_{i=1}^{n} m_i \Delta_i} \tag{2}$$

$$m_{eff} = \frac{\sum_{i=1}^{n} m_i \Delta_i}{\Delta_d} \tag{3}$$

The following step is the evaluation of the equivalent viscous damping, which accounts for the elastic (ξ_{el}) and the hysteretic (ξ_{hy}) damping: ξ_{el} considers material viscous damping, radiation damping due to the foundation system and damping due to non-structural components; ξ_{hy} considers the energy dissipation capacity of the system and depends on the hysteretic behaviour of the structural elements. Various equivalent viscous damping formulations are available in the literature [26,28,29]. The formulation adopted herein [29] depends on the effective period and displacement ductility of the SDOF substitute structure, being the displacement ductility represented by the ratio between design and yield displacement ($\mu_\Delta = \Delta_d/\Delta_y$):

$$\xi_{eq} = \xi_{el} + \xi_{hy} = 0.05 + a\left(1 - \frac{1}{\mu_\Delta^b}\right)\left(1 + \frac{1}{(T_{eff} + c)^d}\right) \tag{4}$$

The parameters (a, b, c, d) depend on the non-linear properties (i.e. hysteretic model) of the structural elements and they are obtained by regression analysis. It is worth noting that, being T_{eff} not available at the beginning of the design process, a first tentative value is necessary, for instance $T_{eff} = 1$ s, and subsequently updated. The hysteretic model considered as a reference herein is the Takeda model [30] whose force–displacement relationship (Fig. 1) is defined by $\alpha = 0.3$, $\beta = 0.6$, $r = 0.05$; the corresponding parameters of Eq. (4) are: $a = 0.249$, $b = 0.527$, $c = 0.761$ and $d = 3.250$.

The yield displacement (Δ_y) corresponds, for single-storey hinged frames, to a linear variation of the curvature from 0 to yield (ϕ_y), from the column tip to the column base; for multi storey structures, a specific formulation of Δ_y will be defined in the following. According to Priestley et al. [26], the yield curvature of rectangular reinforced concrete elements can be related to the properties of the cross-section:

$$\Delta_y = \phi_y \times \frac{H^2}{3} = 2.1\frac{\varepsilon_y}{B} \times \frac{H^2}{3} \tag{5}$$

B and H are the cross-section depth and the column height respectively; ε_y is the yield deformation of the longitudinal reinforcement.

The equivalent viscous damping is used to scale the elastic displacement spectrum (S_{D_el}) for damping values different from 5%. According to EN 1998-1 [24], this reduction is:

$$\eta = \frac{S_{D\_el}(\xi_{eq})}{S_{D\_el}(\xi_{eq} = 0.05)} = \sqrt{\frac{0.10}{0.05 + \xi_{eq}}} \tag{6}$$

The substitute structure effective period (T_{eff}) is the period of the damped displacement spectrum ($S_{D\_el}(\xi_{eq})$) corresponding to the target displacement (Δ_d). From T_{eff} it is possible to evaluate the effective stiffness (k_{eff}), associated to the substitute structure

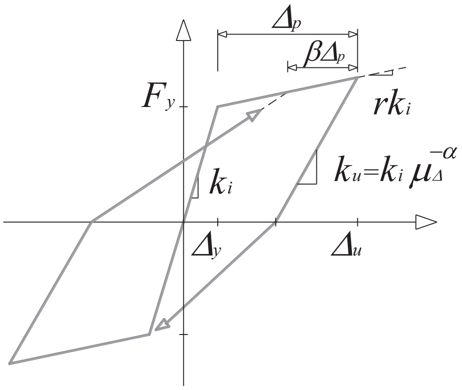

Fig. 1. Takeda hysteretic model.