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A Short Note on the Different Methods of Seismic Analysis

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Abstract

According to modern seismic codes, different methods of analysis can be adopted to assess the seismic behavior of civil structures, starting from a very approximate linear static method up to a rather comprehensive non-linear dynamic analysis. Since the choice of the designer is usually driven both by simplicity of modelling and speed of calculation, the more simplified methods are usually preferred to the more complex in the design practice. The less rigorous the method, however, the rougher the results. To avoid underestimating the actual seismic demand and to design safe buildings regardless of the type of analysis adopted, results from approximate methods should be more conservative than those obtained from the more rigorous methods. This is not always guaranteed by seismic codes. On the other hand, adopting more rigorous methods of analysis, like the non-linear ones, at least when irregular and complex structures are involved, should be encouraged by seismic codes, also avoiding lacks or inadequacies in code provisions.

Keywords: Seismic analysis; Safe design; Seismic behavior; Code-based seismic design

Abbreviations: NLSA: Non-Linear Static Analysis; MRSA: Modal Response Spectrum Analysis; LFM: Lateral Force Method; NLTHM: Non-Linear Dynamic Approach

Introduction

Assessing the seismic behavior of existing and new constructions is a main concern for civil engineers. Seismic codes typically allow different kinds of analyses to this purpose, ranging from the simplest (based on conventional static forces applied to elastic-linear systems) to the more rigorous (accounting for the ductile behavior of structural members and applying real ground motions at the base of the building) [1]. Basically, four types of code-compliant analyses can be performed according to codes of practice [2,3], that differ from each other in the behavior of the structure (linear or non-linear) and in the balance of forces (static o dynamic). A linear-elastic behavior of the structure is assumed by both the Lateral Force Method (LFM) and the Modal Response Spectrum Analysis (MRSA), while a non-linear (dissipative) structural behavior is assumed by the Non-Linear Static Analysis (NLSA), also called Pushover Analysis, and by the Non-Linear Time-History Analysis (NLTHA). On the other hand, a static balance of forces is assumed in LFM and NLSA, while a dynamic equilibrium is accounted for in MRSA and NLTHA. Apart from some limitations to the use of the LFM, the designer can freely choose among these methods.

Because static analyses are simpler to be carried out than dynamic and the motion equations of linear systems are faster to be solved than those of non-linear systems, usually the designer prefers to consider static rather than dynamic approaches and linear rather than non-linear behavior. Therefore, among the code-based seismic methods of analysis, the static approaches are usually preferred and, in particular, the static-linear approach (LFM) is quite commonly adopted. Being more approximate and thus less precise, the static methods are expected to be more conservative than (or, at least, as conservative as) the dynamic methods, which are more rigorous in considering the dynamic balance of forces. For the same reasons, linear methods cannot be less conservative than non-linear methods, since the latter more closely capture the real behavior of the structure. Sometimes, design codes are not able to guarantee that the more approximate analyses lead to a safe design, as shown in [4,5].

On the other hand, the non-linear dynamic approach (NLTHM), which is the most rigorous way to study the seismic behavior of structures, is still the less used in practice, due the considerable difficulties in modelling and the significant computational burden. Its use should be encouraged and supported much more by codes of practice [6-11].

Complexity and Conservativeness of Seismic Analysis Methods

Let's consider the shear-type single-story frame of mass *m*, lateral stiffness *k* and damping ratio ξ, depicted in Figure 1a, and let's assume both an indefinitely linear elastic behavior (Figure 1b) and an elastic-perfectly-plastic behavior (Figure 1c). The equations relevant to a linear-static, a linear-dynamic, a non-linear static and a non-linear dynamic analysis of the system in Figure 1a are provided in Table 1. The single-degree-of-freedom oscillator is assumed to have a linear elastic behavior (Figure 1b) when considering the linear static and the linear dynamic analyses, while an elastic-perfectly-plastic behavior (Figure 1c) is assumed for the non-linear static and dynamic analyses.

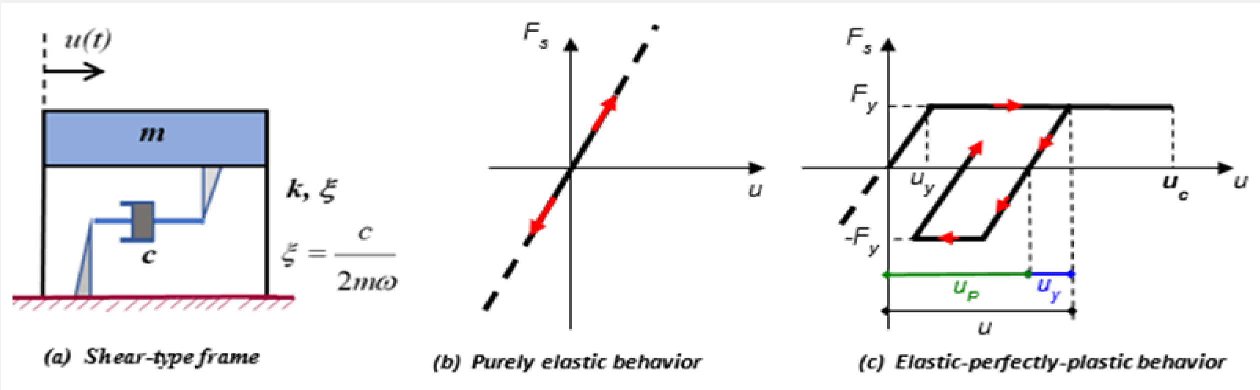

Figure 1: (a) Shear-type frame with purely elastic (b) or elastic-perfectly-plastic (c) behavior.

Table 1: Different types of analysis and related equations (with reference to the system in Figure 1).

Type of Analysis	Equations
Linear static	$ku = F_{STA}$ (1)
Linear dynamic	$\ddot{u} + 2\xi\omega\dot{u} + \omega^2 u = -a_g(t)$ (2)
Non-linear static	Elastic range $if\,\|u-u_p\| < \frac{F_y}{k} \quad k(u-u_p) = F_{STA}$ (3*a*) Plastic range $if\,\|u-u_p\| = \frac{F_y}{k} \quad \mathrm{sgn}(u-u_p)F_y = F_{STA}$ (3*b*)
Non-linear dynamic	Elastic range $if\,\|u-u_p\| < \frac{F_y}{k}$ $or\,\|u-u_p\| = \frac{F_y}{k}\, and\, \mathrm{sgn}(\dot{u}) \neq \mathrm{sgn}(u-u_p)$ $\left\{ \begin{matrix} \dot{u}+2\xi\omega(\dot{u}-\dot{u}_p)+\omega^2(u-u_p)=\mathrm{sgn}(u-u_p) \\ \dot{u}_p=0 \end{matrix} \right.$ (4*a*) Plastic range $if\,\|u-u_p\| = \frac{F_y}{k}\, and\, \mathrm{sgn}(\dot{u}) = \mathrm{sgn}(u-u_p)$ $\left\{ \begin{matrix} \ddot{u}+\mathrm{sgn}(u-u_p)\frac{F_y}{m}=-a_g(t) \\ \dot{u}_p=\dot{u} \end{matrix} \right.$ (4*b*)

It is to note that the code-compliant linear-dynamic method MRSA [2] does not require the integration of the motion equations, that is eq. (2) for a SDOF, since it is based on a procedure that combines the contribution of the more significant modes, as obtained by a preliminary modal analysis, and the use of the design response spectrum. In fact, a linear-dynamic analysis, based on the integration of the motion equations under spectrum-consistent ground motions, is also allowed by codes [3].

It should also be noted that when a non-linear static analysis is performed on a SDOF system like this in Fig.1, a static force equal to the force at yield F_y would lead the system to the ultimate displacement u_c (capacity), as can be inferred by equations (3a-3b) in Table 1. On the contrary, when a ground acceleration $a_g(t)$ is applied to the base of the oscillator and a non-linear dynamic analysis is carried out, the system can withstand forces even much higher than F_y, thanks to the alternating trend of the external force and to the role of the inertia load in the force balance, see equations (4a-4b) in Table 1.

The simple example considered in Figure 1 and Table 1 shows that as we go from linear to non-linear and from static to dynamic methods, the difficulties in modelling and the computational complexity typically increase (Table 2). Of course, when three-dimensional multi-story buildings are involved, modelling the non-linear behavior of the structure may become very challenging due to the need of considering ductile and dissipative constitutive curves for each structural member. On the other hand, when a dynamic analysis of non-linear multi-degree-of-freedom systems is performed the computational burden may increase enormously. In this case, in fact, the need to find suitable sets of spectrum-consistent earthquakes and to solve systems of non-linear differential motion equations adds to the effort of modelling the non-linear behavior of the structure [7-11].

What is the advantage of using more comprehensive and complex methods of analyses for the designer? The advantage is in terms of accuracy of results (Table 2) which should entail, finally, cost saving. Obviously, all the methods of seismic analysis should lead to a safe design. To achieve this goal, rougher methods need to give more cautionary results than more stringent methods, to compensate for uncertainty of results. If this is not the case, safety would be put at risk. In Table 2, an up-to-top arrow indicates that the conservativeness extent is expected to increase as the precision of the analysis decreases.

Table 2: Complexity and conservativeness of different kinds of analysis.

Analysis type	Method (EC8)	Difficulty in Modelling	Computational complexity	Accuracy of results	Conservativeness extent
Linear Static	LFM				
Linear Dynamic	MRSA	↓ increase	↓ increase	↓ increase	↑ increase
Non-Linear Static	NLSA				
Non-Linear Dynamic	NLTHA				

Based on the assumption that the contribution of the first mode is predominant, the simplest method LFM applies to the building a pattern of conventional static forces that generates the shape of the first mode. Comparing the results obtained from this method with those given by the more precise MRSA, in [5] it was shown that the LFM may lead to underestimating seismic effects, especially when applied to non-regular-in-plan buildings. This is due to a loophole in the EC8 seismic code, that may dangerously affect the safety of buildings under seismic loads.

On the other hand, the top-to-up arrows in Table 2 show that, despite the difficulty in modelling and the computational effort, the more rigorous non-linear analyses lead to more accurate results which can generally imply also cost saving. Based as it is on a non-linear model of the structure and on the integration of the motion equations under suitable real earthquakes [12], the NLTHA is the most comprehensive method of seismic analysis. Due to the difficulties involved and to the high skills required to the designer, however, this powerful method of analysis is still the least used in practice. Some inadequacies of the seismic codes in defining the spectrum-consistent earthquakes to be used in the numerical analysis may even contribute to ward off the designer from this kind of seismic analysis, as showed in [6].

Conclusion

Some aspects related to complexity of modelling, accuracy of results and conservativeness extent of the methods of seismic design allowed by seismic codes have been briefly discussed. Basically, four main approaches are provided by codes of practice, ranging from a very approximate linear static method to a comprehensive non-linear dynamic analysis. In general, the designer can choose the method of analysis to adopt without any constraint, apart from some not extremely restrictive conditions the codes impose to apply the linear static method. To ensure a safe design, rougher methods are expected to be more conservative than -or at least as conservative as- more stringent methods. In the face of the greatest simplicity of calculus, in fact, the price to be paid may be a gross estimate of the seismic effects. This should occur, however, on the safe side, which means that rougher methods are expected to overestimate -and never underestimate- seismic effects. Seismic codes should guarantee a safe design whatever the method adopted by the designer, particularly when less accurate methods are used.

The advantage in adopting more rigorous methods of analysis (like the non-linear static or the non-linear dynamic ones), in fact, lies in the accuracy of the results and, finally, in the cost saving. Seismic regulations should encourage the use of the more rigorous approaches, avoiding deficiencies in code rules.

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