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# Equivalent uniform damping ratios for linear irregularly damped concrete/steel mixed structures

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ABSTRACT

Structures consisting of two parts, a lower part made of concrete and an upper part made of steel are investigated. In code-based seismic design of such structures several practical difficulties are encountered, due to inherent differences in the nature of dynamic response of each part. The specific issue addressed here is the analysis complications due to the different damping ratios of the two parts. Such structures are irregularly damped and have complex modes of vibration, so that their analysis cannot be handled with readily available commercial software. This work aims at providing a simple yet sufficiently accurate methodology for handling the damping irregularity of such structures, by proposing an overall equivalent damping ratio that can be applied to the complete structure for obtaining its dynamic response. This is achieved by first transforming MDOF irregular structures into equivalent 2-DOF oscillators, using the first mode characteristics of each part, and then using equivalent uniform damping ratios that are derived by means of a semi-empirical error minimization procedure. Thus, available commercial software can be applied for seismic analysis and design and the provisions of existing seismic codes can be adhered to.



## 1. Introduction

Aim of the present work is to deal with issues arising from the in-height irregularity of elastic structures consisting of two parts, a lower and an upper part. The lower part is usually called primary structure or substructure and is denoted with the letter p, while the upper part is referred to as secondary structure or superstructure, is denoted with the letter s, and is founded on the top of the primary one. The response characteristics of the two parts when the structure is subjected to dynamic excitation are irregular. This irregularity may arise from the different lateral stiffness systems and/or energy dissipation mechanisms of each part, for example a substructure equipped with bracings and a superstructure configured as a moment resisting frame structure. Another reason often leading to different dynamic response in the two parts may be the material distribution over the height of the structure, e.g. primary structure made of concrete and superstructure made of steel, leading to different damping properties of the two parts. In all these cases the irregularity induced to the structure leads to complex response when the structure is subjected to dynamic loading, such as earthquake excitation.

Several applications of such structural configurations are encountered in practice. A frequent use is in stadiums where the spectator seats are made of concrete frames or concrete dual wall-frame systems and are also used to house auxiliary facilities of the stadium, while cover of the seats is often provided by steel trusses resting on the top of the concrete part, as in Fig. 1. Another possible application is the case of adding storeys to existing reinforced concrete buildings. The existing building is often underdesigned in terms of seismic capacity; therefore, the additional levels are often configured as light steel frames in order to reduce the additional dead weight and to achieve speed of construction, as in Fig. 2.

In accordance with several practical applications, such as the ones mentioned above, the particular case of structures where the upper part is made of different structural material than the lower part, and thus the two parts have different damping ratios, is investigated here. The investigation is restricted to the case that both parts remain in the elastic range, thus isolating the issue of different damping of the two parts from the one of different energy dissipation mechanisms.

Seismic design codes currently in use, like IBC [1] and EC8 [2], do not include provisions for the analysis of such irregular structures when they are subjected to earthquake actions. The most relevant recommendations in such cases are the ones regarding appendages. As such can be considered secondary structures, whose masses are considerably smaller than the ones of the primary structure they rest upon, like lightweight antennas, chimneys, etc. When the masses of the two parts are of the same order, as in the cases of Figs. 1 and 2, the appendage consideration gives erroneous prediction for the response of the superstructure and completely

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