Our achievements on mutiblock columns and arches

The basic model of impacting blocks was developed by Housner. First we performed simple experiments using granite blocks to investigate the damping effect at uneven connection surfaces between blocks in cantilevers and arches. Results of these experiments confirmed our hypothesis about the inaccuracy of Housner's model for general application. We developed a novel, extended version of Housner's model that is supported by our experimental results [1]. Later these experiments were extended to two- and three block columns.

Based on the new impact model we developed a tool that can analyze a multiple degrees of freedom system made of individual rigid blocks and excited by an arbitrary signal. Movement of a masonry arch or cantilever is complicated by the opening and closing of the surfaces of its rigid blocks. Our tool pays special attention to the identification of such events and considers their influence on global geometry and connections. A substantial amount of work was put into the development of this tool in OpenSees to provide it free for the research community. This approach had to be abandoned eventually because we experienced numerical issues that could not have been solved within the scope of this project. We migrated to MATLAB where we managed to resolve the numerical issues [2,3].

The rocking motion of a two- and three-block column was investigated to verify our numerical model developed for rigid multiblock columns. The experimental results show good agreement with the results obtained from the numerical model [4].

Based on the verified multiblock column model we could investigate the overturning behaviour of multiblock columns for various excitations. It was found that with reasonable accuracy single blocks are more vulnerable than multi-block columns for overturning. This finding helped us to introduce a new design methodology of multiblock columns, which is based on the behavior of single rocking blocks for earthquake excitation. The so called Overturning Curve was generalized for earthquake records, and the overturning acceleration spectrum (OAS) was introduced [2]. In principle, a characteristic OAS can be determined by the statistical evaluation of time history analyses of rocking mechanisms for earthquake records at a given location. Based on the analyses of rigid blocks for 100 earthquake records, it was found that the OAS could be characterized well by one parameter: the "replacement impulse duration" (t_I). The OAS is inversely proportional to the frequency parameter p, introduced by Housner. It was also shown that the replacement impulse durations and the actual impulse durations of the main pulses of earthquake records are highly correlated. A simple design equation was recommended to determine the safety of structures subjected to earthquakes for overturning.

We also investigated the overturning acceleration (response) spectra (OAS) of rigid blocks subjected to double pulses. It was found that for higher accelerations they are well represented by a curve which is proportional to $1/p^2$ (p is the frequency parameter of the block). Using this result it is proposed that for real earthquake records the OAS is approximated by the envelope of three curves, a straight line, one which is proportional to $1/p$, and one proportional to $1/p^2$. These curves depend on two parameters: the replacement impulse duration (t_I), and the replacement impulse-moment duration (t_M), which must be determined numerically for an earthquake record. These observations further strengthen the analogy between the response spectrum analysis of elastic structures and the overturning acceleration (response) spectrum analysis of rocking blocks [5].

We extended our multi-block column model to build a multi-block arch model to investigate the rocking motion of masonry or stone arches consists of rigid blocks.

A new numerical model is developed for planar multi-block arches subjected to earthquakes [6]. The blocks are assumed to be rigid, and every interface between the blocks may split open and may close, i.e. the blocks may impact to each other. During impact both the classical Housner's approach and improved models with lower energy dissipation are considered. The arch model is verified by comparisons to the available results in the literature. Using this new model it was found that the circular arch moves as a four-hinge mechanism typically only at the beginning of excitation, and several cracks split open during motion; furthermore, that modelling a multi-block arch by an SDOF four-hinge mechanism may significantly overestimate its collapse load. While, in accordance with the literature, the overturning curves of single blocks and arches with symmetrically located four hinges are similar; for multi-block arches where several hinges may occur they can be very different.

Our achievements on soil structure interaction (SSI)

A methodology was developed that uses a publicly available European seismic source model and state-of-the-art probabilistic seismic hazard assessment to determine site-specific target response spectra. These spectra can be used to provide appropriate sets of ground motion records for numerical experiments and numerical analyses.

Research efforts on ground motion record selection were focused on improving the definition of the seismic hazard. The previously developed site-specific target response spectra assessment methodology was enhanced with a probabilistic approach to soil amplification. The new approach uses probabilistic seismic hazard assessment and hazard disaggregation to evaluate the hazard curves at the bedrock. Soil amplification is quantified as a frequency and spectral acceleration intensity dependent random variable using data from nonlinear response history analyses on one dimensional representations of soil columns from the bedrock to the surface. Uncertainties in the bedrock hazard and the soil amplification are combined through conditional convolution to describe the surface hazard. Corresponding uniform hazard spectra and conditional spectra can serve as targets for ground motion record selection.

In seismic design, the most accurate method to model soil-structure interaction is the direct approach, where the soil and the structure are represented together [7]. This analysis can be very time consuming and complex, therefore it cannot be used in most of the practical cases. To overcome these difficulties, several simplified models were suggested in the literature [8]–[10]. These models are different for infinite soil half-spaces and finite soil layers. The finite soil layers can be represented by complex lumped parameter models, or e.g. by echo constants introduced by Wolf to consider the refraction at the border of the layers [11]–[15]. Most of the methods do not take into account the finite dimensions of the soil, which results significantly different behavior than the spring-dashpot systems [16]. For an infinite medium, which is used in many cases, there are no eigenmodes, however in practical applications the soft soil is always bounded by rocks. For these cases the soil has eigenmodes and the resonance may influence considerably the response of the system. This question was investigated numerically by FE calculations, and it was found that in certain cases the resonance, which is neglected in the common design process, may significantly enhance the earthquake loads [16]–[18]. In addition in the real cases the radiation damping plays an important role which is not properly taken into account in the simplified models. These phenomena were investigated and the parameter range is defined when this effect must be taken into account [16].

We developed a new model according to a mathematical derivation based on a 2D model for horizontal motion, which includes these effects, and gives close results to the 2D numerical cases. The model needs only a few parameters and based on a physical background. We also gave the analytical solution of this model, which can be used for a new design method [19]. Numerical verification was performed, and the parameter range was determined, where applying a spring-dashpot model instead of the presented new model results in huge errors.

The above new model was extended to 3D and irregular cases. The advantage of using this model is that it contains only very few parameters and results in a 1D problem instead of a 3D one. It was shown that the number of the independent parameters of the model is three:

• the static stiffness of the model K,
• the eigen (cut-off) frequency ωc,
• the ratio η which shows the contribution of the sub models. (For η=0 it gives the mass-spring system, while for η=1 the axially constrained infinite bar.)

Furthermore a simple identification process is presented, which – based on the impedance function – enable us to determine the model parameters by simple closed form expressions.

Our achievements on rocking shear walls

Conventional modal response spectrum analysis needs to be enhanced to provide appropriate results for structures with special flag-shaped hysteresis. We have developed an extended version of a self-centering numerical material model in OpenSees. Using this new material model we analyzed the inelastic response spectra of self-centering systems and proposed a reduction factor that can be applied in modal response spectrum analysis. Our results enable the preliminary design of single degree of freedom self-centering structures. Reduction factors due to the flag-shaped hysteresis curve were determined for given yield strength reduction factors. Furthermore, an interpolation method was implemented in a Matlab and OpenSees based algorithm to achieve the given ductility facture curves to be able to refine the design method of single degree of freedom systems.

The aforementioned assessments used results from millions of numerical time history analyses. We utilized Superman, the HPC cluster at BME (supported by TÁMOP – 4.2.2.B-10/1-2010-0009 project) for our calculations. Development of numerical models in OpenSees for rocking shear walls started with the help of MSc students. We compared numerical response with experimental results from the literature to evaluate different modelling approaches.

In spite of the enormous computational efforts our results are not conclusive yet and further research must be conducted to achieve a reliable design methodology of rocking shear walls.

Our achievements on floor vibration

Our analytical approach was also applied for the dynamic analysis of floors. Note that this problem was not included in the original proposal, however, it turned out that our mathematical model developed for SSI can be extended for floor vibration.

Vibration control is a major consideration in the design of light-weight floors. The response (acceleration or speed) of structures subjected to human- or machine-induced vibration is compared to the tolerance limit of human comfort [20]–[23]. Both numerical and experimental observations show that the response is typically dominated by a single mode, and the analysis can often be simplified to a single degree of freedom (1DOF) system.

We showed that the approaches recommended in the literature is working only in a certain parameter range. For long plates (and not long orthotropic rib-stiffened plates) these design methods may lead to 2–4 times higher accelerations than the real values because of the presence of the so called radiation damping. In an economic design this effect must be taken into account. A new method was developed and verified which contains this phenomenon [24], [25].

Two of the team members, Tamás Ther and Zsuzsa Borbála Pap defended their PhD theses with the support of the OTKA project under the supervision of the PI.

Note that 5 of our publications are in the D1 category.

Summary

A new model was developed for the analysis of multiblock systems. The basic building block of the model is the improvement of Housner's rocking model, where we could give a physical explanation why this classical model underpredicts the motion of the blocks. Based on the numerical results of our model and on our experiments a new design methodology was developed for multiblock columns and arches. We also showed that the classical approaches of modelling the soil structure interaction can be very inaccurate under certain parameter ranges, and a brand new model was developed, which is based on an axially restrained infinite bar. The novelty of the model is that it can take into account the so called "radiation damping" directly, which was missing in the classical models. A surprising application of this model is the vibration control of floors, where radiation damping also plays an essential role.

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