Backstay Effect

Basement Modeling in Tall Buildings

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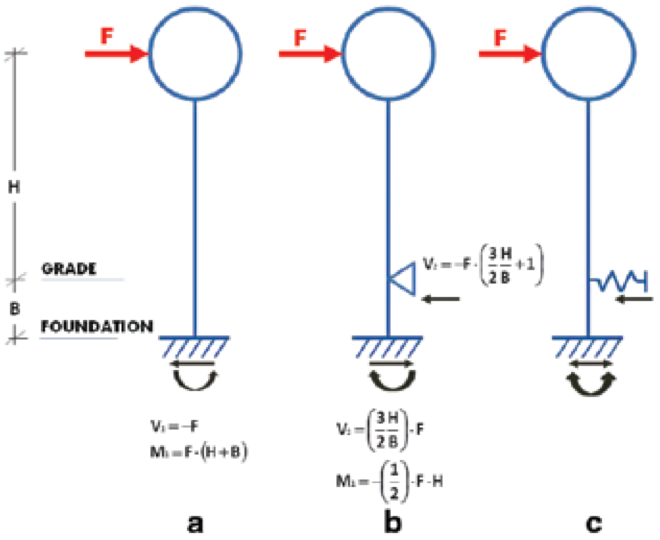

Figure 1: Modeling options for base condition.

One of the least understood aspects of modeling building structures is dealing with at- and below-grade components. This includes soil-structure interaction, but also the question of which below-grade structural elements should be included in a lateral model and what is an accurate representation of the base conditions.

The focus of this article is what is most commonly referred to as the backstay effect. Traditionally, lateral systems have been viewed as simple cantilever beams fixed at the base. While this analogy is reasonable for the above-grade structure, a more accurate analogy would also include the effects of the below-grade structure, which behaves like a backspan to the cantilever. In this analogy, the lateral system is viewed as a beam overhanging one support, where that support is created by the at-grade diaphragm and foundation walls.

The backstay effect is not limited to restraint at the grade level. Backstay effects are also seen at setbacks with changes to the lateral system, the most common example being lower level podiums. They are often very large in plan and introduce new lateral elements, and are therefore significantly stiffer than the set-back structure above. Backstay effects are also impacted by multiple basement levels. For simplicity of explanation, this article will focus on the most common example which is the effect of the ground floor diaphragm in contributing to backstay effects. The concepts can be extended to all conditions where backstay effects occur.

Backstay Effect

Backstay effects are most noticeable in buildings with discrete lateral systems, such as shear walls, as opposed to distributed lateral systems. Building height is also a major factor in the magnitude of the backstay effects. For the purposes of illustration, this article focuses on a high rise shear wall building with a single basement.

For a typical building with one or more below grade levels, the perimeter basement walls create a very large and laterally stiff box. The ground floor diaphragm engages this box and integrates it into the lateral system. Sticking with the beam analogy, the result is an effectively larger beam section below grade. This results in shedding of lateral load from the main lateral force resisting system (LFRS) to the basement walls. Overturning and shear are shared between the perimeter walls and core rather than isolated beneath the building core. Conceptually this is fairly straightforward. The complexity arises in properly modeling the change in section, and capturing an accurate distribution of internal forces and external reactions.

The degree to which lateral loads are transferred into the foundation perimeter is dependent on many variables, many of which there is limited certainty about, as they are not specified or controlled in a typical project. It is therefore fair to ask if it is more conservative to simply ignore any backstay effects and model the building core as an isolated element. However, it can be shown that in many cases the backstay effect will create higher demands in some structural elements, in particular shear in the main LFRS below grade as well as the backstay diaphragms, and therefore cannot be ignored.

Figure 1 is a stick diagram presenting some of the possible options for modeling the base conditions of a core wall building. The building is of height H with a basement of height B. The most traditional model, a simple cantilever, is shown in *Figure 1a*. It is clear that the maximum shear is V = F. The extreme case of the backstay effect is shown in *Figure 1b*. In *Figure 1b* the ground floor diaphragm and perimeter foundation are very stiff and are therefore modeled as a pin. Statics shows that the maximum shear in the core now occurs below grade with V = 3H/2B F. The

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overall base shear has not changed, but the backstay effect may create conditions with much higher demands than anticipated in certain elements. It can also be shown that the base overturning moment in the core has been reduced and redistributed to the perimeter foundation walls.

Although *Figure 1b* shows dramatic increases in shear, this is overly conservative for most conditions. The true restraint at the ground floor is far from rigid and may range from very stiff to almost non-existent. A more realistic model is one in which the ground floor restraint is modeled as a spring, producing results somewhere between *Figures 1a* and *1b*. *Figure 1c* shows this option.

The complexity of an accurate model lies in the fact that the spring in *Figure 1c* represents the cumulative stiffness of numerous elements in the building structure and supporting soil. A partial list of elements represented by the ground floor spring would include: diaphragm to core connection, diaphragm stiffness, diaphragm to basement wall connection, basement wall stiffness, foundation stiffness, and passive soil resistance against the basement wall.

Ground floor diaphragms are often thick concrete plates with high relative stiffness. However, this stiffness may be reduced by cracking, bond slip, and discontinuities such as large openings or slab elevation changes. In addition to the stiffness of the diaphragm itself, the connections at each end must be considered for their ability to transfer the backstay shears. The same can be said for the basement walls which will have varying stiffness dependent on the same factors.

The overall stiffness of the diaphragm and basement wall system is also affected by the supporting foundation elements. Differences in relative stiffness between core and perimeter wall soil support conditions may magnify or lessen backstay effects.

The passive resistance provided by the soil on the basement wall face in the direction of force should also be considered. This component is typically small relative to the other elements and may possibly be neglected in many cases. In addition, this force is present only in the compression cycle of loading and should be modeled as such.

Clearly there are many parameters to consider. In most cases, the best that can be done is to model all contributing elements and make an educated estimate of the element stiffnesses. The number of possibilities is too numerous for a prescriptive approach that will work for all buildings, which is perhaps why there is little literature on the subject. Most building codes provide requirements for loading and design of structural elements, but rarely provide detailed guidance on modeling procedures. A very good resource for an in depth discussion of the backstay effect and recommendations for modeling is *Modeling and Acceptance Criteria for Seismic Design and Analysis of Tall Buildings*, PEER/ATC 72-1, which is available as a free download from the PEER (Pacific Earthquake Engineering Institute) website.

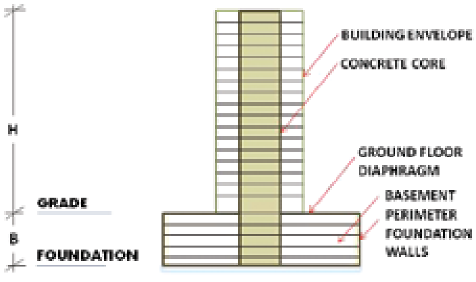
The backstay concept is more familiar to engineers working in high seismic regions and has had less attention in other regions. The concepts, however, are applicable for both wind and seismic loading.

Modeling

A reasonable first step may be to assess whether the backstay effect is a consideration for the building under investigation. A quick study of the parameters that create the backstay effect may quickly rule out the need for a more in depth analysis. The building system or configuration may also determine the potential for backstay effects.

For buildings where backstay effects need to be considered, it will most likely be necessary to consider multiple scenarios. Both an overestimation and underestimation of backstay effects can produce underestimates of demand. For example, overestimating backstay restraint may underestimate the overturning demand at the base of the main LFRS. The common approach is to consider reasonable extremes for both conditions and design each element for the bounding condition. This is typically referred to as bracketing.

The backstay diaphragms must be modeled as semi-rigid elements. Semi-rigid elements have stiffness taken from the material and geometric properties of the slab. Any large discontinuities in the slabs should be modeled, and a mesh size should be chosen that produces accurate results. To account for cracking, bond slip, interface slip, and other unknowns, the stiffness of the slab should be reduced for both shear (GAv) and flexural (EI) stiffness. Similar modeling guidelines and stiffness reductions should also be applied to basement wall elements.



Typical concrete core building configuration.

Soil stiffness should also be bracketed, typically starting with recommendations provided by the project geotechnical engineer. The supporting stiffness under all elements should be taken at an upper and lower bound, and passive resistance provided against the perpendicular wall should also be bracketed if it is modeled.

PEER/ATC 72-1 Table A-2 and Table A-3 provide recommended upper and lower bounds for bracketing the stiffness of the above elements. PEER/ATC 72-1 also recommends that elements outside of the backstay influence (primarily tower elements) need not be bracketed and should be modeled with the same assumptions used for their design. Since these recommendations are intended for buildings in high seismic regions, it may be appropriate to adjust the recommendations for wind controlled design to account for primarily elastic behavior.

Due to the complexity of capturing backstay effects in the analysis, it may be desired to eliminate the phenomenon in the actual building. This can be accomplished by isolating the LFRS from the foundation elements by providing lateral joint at the backstay diaphragms. Typically this is done by providing a corbel or similar detail at the diaphragm to shear wall interface.

Conclusion

Ignoring the contribution of at- and below-grade structural elements in lateral models may underestimate demands in key elements. A quick initial study may be enough to determine if a more in-depth model, which includes backstay elements, is justified. If backstay effects are included in the model, current practice is to bracket stiffness parameters and design for a bounding solution. Unfortunately, this approach results in overdesign of at least some members. As knowledge of the topic increases, bracketing parameters will be refined and increase the efficiency of designs.▪