Understanding strength error consequences in seismic design

When it comes to structural design, the engineers need to account for the variability in material strengths, load estimation, etc. For gravity driven loads such as structure dead load, live load due to trucks, etc., the consequences of overestimation of design strength (unconservative design) can be disastrous. Although still important, this is not as critical in a seismic environment. On the other hand, underestimating the upper bound demands due to overstrength can have serious implications. We explain the rationale for this as follows.

Consequences of overestimation of design strength

If the basic design strength has been overestimated, the system will hinge or reach its design force capacity earlier than anticipated. Assuming the equal displacement principle to be valid, this leads to (see Figure 1):

$\Delta_{ea} < \Delta_{eh}$ & $\Delta P_a < \Delta P_h$ (Displacements)

and,

$\mu_{\Delta a} < \mu_{\Delta h}$ $[\mu_{\Delta} = \Delta_T / \Delta_e = (\Delta_e + \Delta_P) / \Delta_e = 1 + \Delta_P / \Delta_e]$ (Displacement ductility)

This means that the actual system will need to undergo more plastic deformation and somewhat higher ductility if the design strength has not been grossly overestimated. Hence, for a system that has been appropriately detailed for ductility, the system will experience more plastic deformation but will not have significantly deteriorated seismic performance or collapse. This is contrast to gravity design, where having design capacity lower than that required to resist applied loads will likely cause structural failure or even collapse.

Consequences of underestimation of overstrength capacity

It is extremely important to capture the overstrength capacity of the earthquake resisting system (ERS) to safeguard against brittle failure mechanisms (e.g. shear, joint shear, etc.). In addition, the flexural failure of elements / zones of elements (e.g. capbeams, column zones outside of plastic hinge regions, etc.) not detailed for ductility needs to be suppressed. Such elements or failure mechanisms require that ultimate capacities are larger than the upper bound demands that can be generated due to unintended sources of overstrength (e.g. material base strength higher than assumed design strength, strain hardening in reinforcement, etc.). Failing to capture the upper bound overstrength of the system will lead to an unconservative design, which will give rise to undesirable brittle failure modes. This includes, but is not limited to column shear failure, joint shear failure, plastic hinging / shear failure of capbeams, foundation hinging or failure, etc. The underestimation of overstrength in the ERS leads to the violation of the capacity design principle, which desensitizes the ERS to seismic demands higher than the design values.

Conclusion

The overestimation of design strength may lead to more plastic action and damage in the ERS. However, for well-detailed structures, it is unlikely to lead to significant performance deterioration. The consequences of underestimation of overstrength capacity are much more serious as it can give rise to brittle failure modes, which can result in significant performance degradation and even collapse without warning.

Reference

Seismic design and retrofit of bridges – Priestly, Seible and Calvi (1998)

OVERESTIMATION OF DESIGN STRENGTH

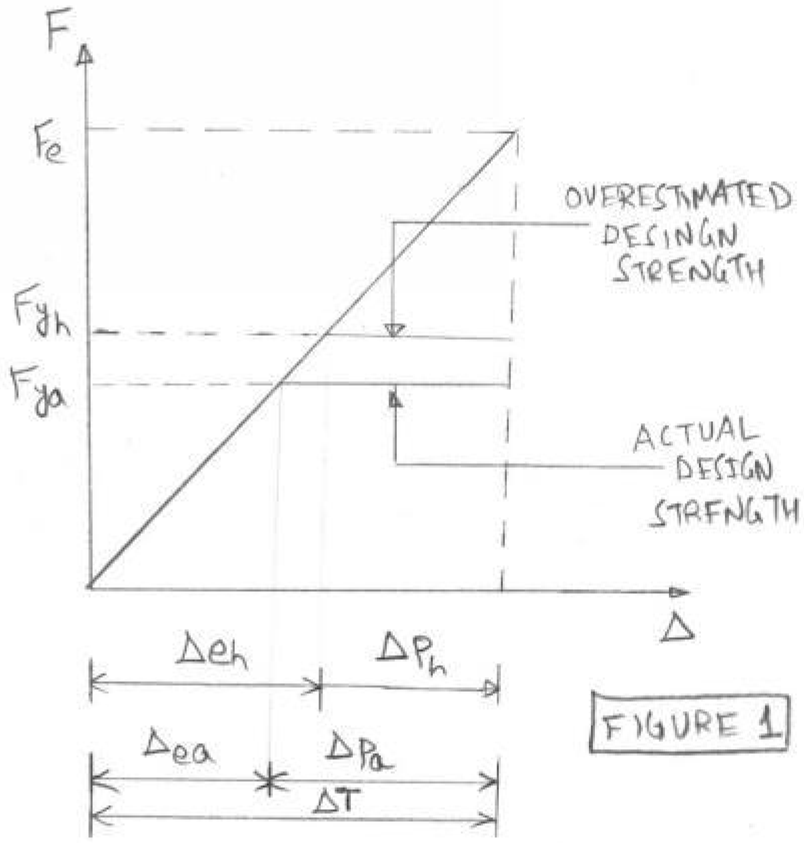

FIGURE 1

Fe : ELASTIC FORCE LEVEL

Fyh : DESIGN STRENGTH FOR ACTUAL SYSTEM (OVERESTIMATED)

Fya : TRUE DESIGN STRENGTH FOR ACTUAL SYSTEM

Δeh/Ph : ELASTIC/PLASTIC DISPLACEMENT (OVERESTIMATED STRENGTH)

Δea/ΔPa : ELASTIC/PLASTIC DISPLACEMENT (ACTUAL STRENGTH)

ΔT : TOTAL DISPLACEMENT

UNDERESTIMATION OF OVERSTRENGTH CAPACITY

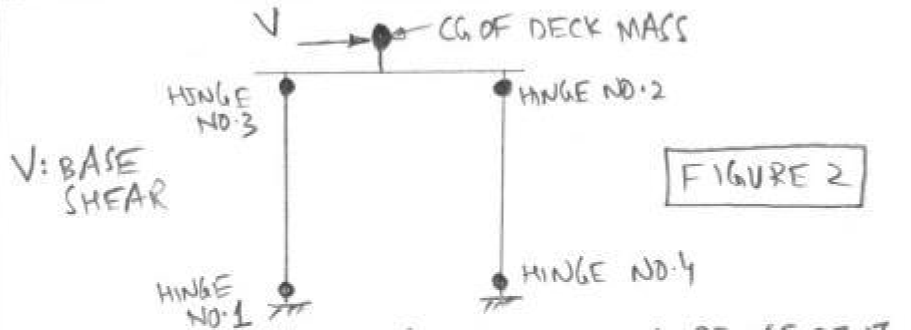

FIGURE 2

TYPICAL TWO-COLUMN BRIDGE BENT

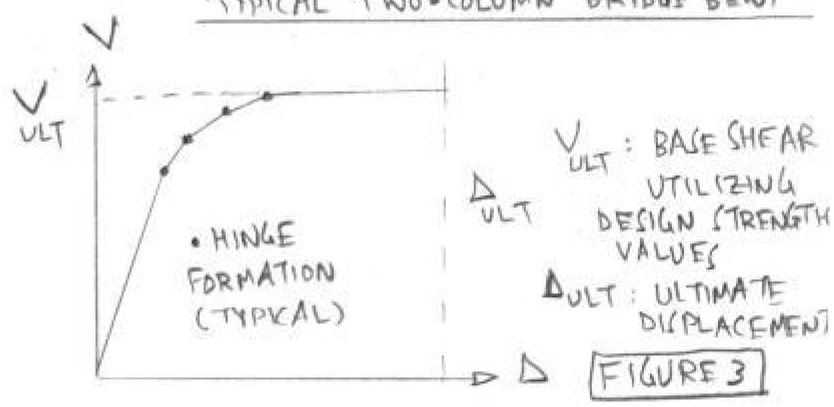

FIGURE 3

NOTIONAL BASELINE PUSHOVER

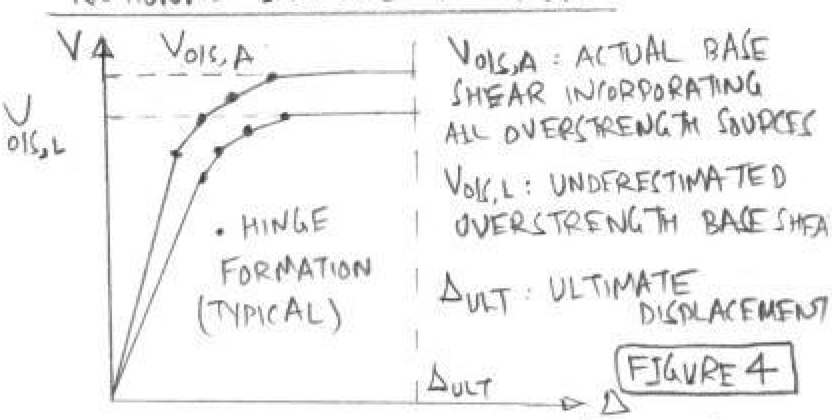

FIGURE 4

NOTIONAL PUSHOVER INCORPORATING OVERSTRENGTH