SCALING IN EXPERIMENTAL INVESTIGATIONS

Amit H. Varma
Associate Professor
School of Civil Engineering and Bowen Laboratory
Purdue University

REASONS

- Prototype
  - too large
  - too complex
  - too many parameters
- Experimental
  - space limits
  - limits of loading capability
  - limits of boundary conditions achieved
  - limits on funds / no. of specimens vs. parameters
- Precedence
  - Ubiquitous
  - Common in structural engineering research
  - Bridges, buildings, special structures etc.

ORIGIN OF SCALING OR SIMILITUDE LAWS

- Complicated laws used to related scaling in terms of fundamental dimensions (mass, time, length)
- Needed for small-scale tests (1:5 or higher)
- Becomes very complicated very quickly, for example our units of force are kg-m/s^2 involving all three units of mass, time, and length
- Used in the 60-80s for small-scale tests that proved qualitative and helped develop / verify theory
  - Krawinkler (Stanford), Sutton (Purdue), Sozen (Illinois), Moehle (Berkeley), Wallace (OU)

APPLICATIONS OF SCALING

- Some aspects of behavior scale well
  - Structural mechanics of members
    - plane sections remain plane and perpendicular
    - linear elastic behavior
    - ductile failure modes (yielding, spread of plasticity)
- Some aspects do not scale well
  - Structural mechanics of connections, interfaces, energy dissipating aspects
    - brittle failure modes, e.g., buckling, fracture, fatigue, debonding, bond failure.
    - non-conservative or path-dependent phenomena, e.g., friction losses, cyclic degradation due to material softening, damping.

WHY DO SOME ASPECTS NOT SCALE WELL ?

- Because of parameters affecting structural mechanics of connections, interfaces, energy dissipating aspects:
  - Fabrication methods, techniques, and end products do not scale well, e.g., welding methods do not scale well
  - Residual stresses and imperfections produced by fabrication methods do not scale well
    - Both of these have a significant influence on inelastic column buckling behavior but they do not scale well.
  - Material fracture properties do not scale well, e.g., the fracture stress/strain of a 1 in. plate may be significantly different from that of 3/16 in. plate of the same material.
  - Bond, development length, transfer length, bolt fracture stress, material ductility do not scale well.
  - Friction and other non-conservative energy dissipating mechanisms also do not scale well.

USE OF SCALING IN STRUCTURAL RESEARCH

- Scaling is done and used commonly in structural engineering.
- Not similitude type scaling, but what I will term structural scaling, i.e., scaling while considering the expected structural behavior and failure modes
- If the specimen is going to have simple structural behavior with a ductile failure mode, scaling can be used without reservation to develop and test specimens.
  - The objective of such tests should be identify the expected failure mode and behavior.
  - The failure mode should be re-evaluated to consider its applicability to larger scales
  - For example, tension or flexural strength scale well. But ductility or rotation capacity of the beam hinge may not!

USE OF SCALING IN STRUCTURAL RESEARCH

- If the specimen is going to have a brittle failure mode, e.g., global buckling of columns, pullout of dowel bars, fracture of welds, brittle shear failure
  - structural scale tests can be done to identify behavior, limit states, etc.
  - larger-scale tests may be required depending on the application and the repercussions of the failure.
  - For example, in seismic design, connections are required to be tested as close to full-scale as possible. This is due to the non-scalability of these phenomena and the repercussions of failure.

USE OF SCALING IN STRUCTURAL RESEARCH

- Then, there are some that show ductile behavior but include non-conservative phenomena
  - For example, for a wide-flange composite girder, the level of partial composite action, the behavior of the steel-concrete interface, and the ductility or slip demand on the shear connectors may not scale well.
  - In such cases, some large-scale or near full-scale tests may be required to provide closure to the findings from the reduced scale tests

USE OF SCALING IN STRUCTURAL RESEARCH

- What is structural scale model?
  - A structural scale model satisfies the following:
  - (1) The scaled model would still represent something that may be built and used in similar construction or systems, e.g., a W8 column may represent a W14 column, but not a jumbo column.
  - (2) The scaled model would be built using the same fabrication methods and technologies as the prototype without requiring special or significant changes.
  - (3) The scaled model would be built using structural materials that are of the same type and behavior as the prototype,
    - e.g., structural plates go from 3/16 in. upwards. Anything less than a ¼ or 3/16 in. will be sheet metal and give a different behavior due to different residual stresses, imperfections etc. from completely different fabrication processes.

WHAT IS A STRUCTURAL SCALE MODEL?

- Typical concrete is built using aggregate from 3/4 - 1.5 in. in size. As long as the scaled specimen concrete is using aggregate about ½ in. size or comparable in the mix design without having to worry about concrete placement, that should be fine.
- (4) The structural scale model will have similar residual stresses, imperfections, frictional interfaces, as the prototype.
- (5) The structural scale model will be designed using the same methods and equations as the prototype, and used to prove the hypothesis that the design equations predict strength conservatively.

U.S. RESEARCH PRACTICE

- In the U.S. for the past 20 years, the push has been for large-scale tests of non nuclear applications primarily due to seismic design and cyclic ductility / fracture considerations (whereby the designs are based on energy absorption capability)
- For Nuclear structures, FOSID is the design basis; thus ductility is not relied upon for design basis and structural scale tests are acceptable
- Typically if fracture is not the limit state, and non-conservative phenomenon do not contribute significantly:
  - 1/3 scale models are acceptable and good for prototypes that are very large to begin with
  - 1/4 scale is OK, but supplementary testing at large scales or testing of individual components to show adequate scaling of local phenomenon will be required
  - Anything below that will be small scale, unless the prototype is so large that even 1/5 or lower scale is a realistic structure built using similar fabrication technologies.

SUMMARY OF STRUCTURAL SCALE MODELS

- (1) The scaled model would still represent something that may be built and used in similar construction or systems.
- (2) The scaled model would be built using the same fabrication methods and technologies as the prototype without requiring special or significant changes.
- (3) The scale model would be built using structural materials that are of the same type and behavior as the prototype
- (4) The structural scale model will have similar residual stresses, imperfections, frictional interfaces, as the prototype.
- (5) The structural scale model will be designed using the same methods and equations as the prototype, and used to prove the hypothesis that the design equations predict strength conservatively.