Impact of Dowel Yield Strength and Modulus of Elasticity on Joint Performance

In common civil and structural engineering design frameworks, such as the American Institute of Steel Construction's (AISC's) Load and Resistance Factor (LRFD) design approach, the modulus of elasticity or Young's modulus of steel is assumed relatively constant at about 29 x 10^6 psi for all steel grades while the designer has significant flexibility in selecting the steel yield strength (steel grade). Such consideration for material strength versus stiffness also has implications for joint performance in concrete pavements and slabs-on-ground. This paper provides general background on this topic and sensitivities of joint performance to these dowel material properties.

Tensile Strength versus Modulus of Elasticity

As succinctly and clearly detailed in an article on the website of the Fabricators & Manufacturers Association, International (FMA 2015) the tensile strength and stiffness (Young's modulus) describe different material properties:

> "Strength is a measure of the stress that can be applied to a material before it permanently deforms (yield strength) or breaks (tensile strength). If the applied stress is less than the yield strength, the material returns to its original shape when the stress is removed. If the applied stress exceeds the yield strength, plastic or permanent deformation occurs, and the material can no longer return to its original shape once the load is removed. A [metal] material's strength is a function its chemical composition, the thermo-mechanical processing route (such as converting from a thick slab to a thin sheet), and subsequent heat treatments. These variables make it impossible to state that one [metal] material is always stronger than another. For example, many aluminum grades are stronger than steel grades, but rarely are they intended for the same application.
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> Stiffness relates to how a component bends under load while still returning to its original shape once the load is removed. Since the component dimensions are unchanged after load is removed, stiffness is associated with elastic deformation. Stiffness of a component is a function of both material and geometry. On the material side, stiffness depends on the modulus of elasticity, also known as Young's Modulus and abbreviated as E. Young's Modulus is the ratio of stress to strain at very small strains. In a stress-strain curve generated during a tensile test, the slope in the linear portion at the beginning is where the modulus is determined. Where it first deviates from linearity is the yield strength (see Figure 1).
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> **Unlike strength, which can vary from [metal] grade to grade or even coil to coil, Young's Modulus is constant for a given metal and is independent of heat treatment, processing, or cold work.** Young's Modulus for steel (29 million psi) is three times that of aluminum (10 million psi). This means that for a fixed geometry, a part made out of steel will be three times as stiff as if it were made out of aluminum. In other words, an aluminum part under load will deflect three times as much as a similarly loaded steel part."

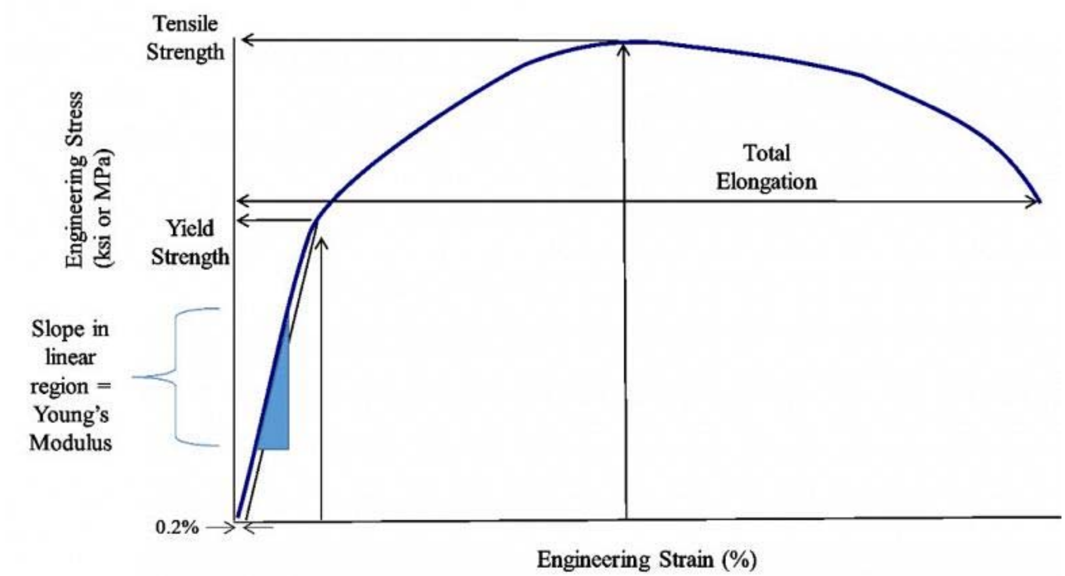

Figure 1. In a stress-strain curve generated during a tensile test, the slope in the linear portion at the beginning is where Young's Modulus is determined. Where it first deviates from linearity is the yield strength. (after FMA 2015).

Joint Performance with Differing Dowel Yield Strength and Modulus of Elasticity

PNA's comprehensive load transfer system design framework, which considers the five response criteria of interest in the dowel-concrete-joint system was utilized to illustrate the impact of a change in dowel yield strength or modulus of elasticity. In short, joints experience performance issues by way of a concrete failure (e.g., concrete bearing stress or shear cone capacity), a dowel failure (e.g., dowel flexural or shear stress), or joint spalling (e.g., joint face impact under too high a joint differential deflection). In common slab-on-ground and pavement dowel system design with steel dowels, joint differential deflection and concrete shear cone capacity tend to control design. Ultimately, though, the response criteria with the lowest factor of safety in design controls.

	Scenario		
Dowel Material Property	**A36 Steel**	**High Yield**	**Low Modulus**
Modulus of Elasticity, psi	29 x 10^6	29 x 10^6	5 x 10^6
Yield Strength, psi	36,000	60,000	36,000
Response Criteria	**Factor of Safety in Design**		
Joint Differential Deflection	1.22	1.22	**0.75**
Dowel Flexural Stress	2.62	**4.36**	**3.93**
Dowel Shear Stress	6.32	**10.53**	6.32
Concrete Bearing Stress	1.83	1.83	**1.15**
Concrete Shear Cone Capacity	1.29	1.29	1.29

Using A36 grade steel, as PNA does for its PD3 Tapered Plate Dowel Baskets, and other typical design inputs for a specific dowel size and spacing results in the factors of safety in the table to the right (see the A36 Steel Scenario). The other scenarios model a single-input change and the resulting factor of safety for High Yield (e.g., 60ksi vs. 36ksi steel yield) and

Low Modulus (e.g., 5×10^6 psi, which is a commonly used value for glass fiber reinforced polymer [GFRP], vs. 29×10^6 psi).

Increasing the dowel material's yield strength (e.g., steel grade):

- Does not change the factor of safety against spalling (e.g., joint differential deflection) or concrete (e.g., concrete bearing stress or shear cone capacity) failures. Because of the relatively low strength of concrete versus steel and with the steel dowel operating within its elastic range, the concrete is expected to fail while the dowel is not expected to undergo permanent or plastic deformation (yield).
- Increases the factor of safety against dowel flexural or shear stress. Because the yield capacity is increased and the design response value unchanged, these factors of safety increase with an increase in yield strength. There is, however, no benefit to use of a higher-grade steel because the limiting response criterion is unchanged; *effectively, specification of a higher yield strength for steel dowel design increases costs without any performance benefit*.

Reducing the dowel material's modulus of elasticity (e.g., stiffness), as one might do if using GFRP instead of steel:

- Does not change the factor of safety against concrete shear cone capacity (which is a function of concrete strength, cover depth, dowel footprint [area in plan view], and other variables) or dowel shear stress (which is a function of area of dowel across the joint, the shear yield capacity, and other variables).
- Greatly reduces the factor of safety against spalling (e.g., joint differential deflection) because the dowel deflects much more under the same load and with all other inputs constant. In this case, the limiting factor of safety is now well below 1.0, meaning that the joint system should be expected to fail unless the dowel size, dowel spacing, or other inputs are changed.
- Increases the factor of safety against dowel flexural stress; the dowels resolve the energy of the loading into the dowel-concrete-joint system through a higher deflection, which works to in-turn reduce maximum stresses in the dowel – for another illustration of this interaction, consider that more of the length of the dowel engages in the load transfer such that the maximum stress value at any given point is reduced because of the greater overall developmental length.
- Reduces the factor of safety against concrete bearing stress. The dowel-concrete interface deflects more because of the lower dowel material modulus such that for the same dowel footprint the concrete compresses more and, thus, breaks down more quickly under repeated loading of the joint.
- For these and other reasons, the National Concrete Consortium (NCC) recommends thorough consideration of such responses when specifying GFRP dowels (see Appendix F – Summary of Studies Concerning Use of FRP Dowels in PCC Pavements in CP Tech 2011).

When in doubt as to the sufficiency of a load transfer design for a specific project, please contact your local PNA engineer or territory manager for a free dowel design and risk assessment.

For More Information

If you would like to request a complimentary project-specific dowel design for your next project or for more information on this or any other topic related to concrete flatwork:

Find Your Local Expert: www.pna-inc.com/where-to-buy

Find Your Distributor: www.pna-inc.com/where-to-buy

General Contact Info: www.pna-inc.com/contact-pna

References

FMA 2015, "The difference between stiffness and strength in metal," Daniel J. Schaeffler, https://www.thefabricator.com/article/metalsmaterials/the-differences-between-stiffness-and-strength-in-metal.

CP Tech 2011, "Guide to Dowel Load Transfer for Jointed Concrete Roadway Pavements," Dr. Mark Snyder, Concrete Pavement Technology Center.