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New Jersey Department of Transportation
Bureau of Research
Technical Brief

Design for Deflection Control vs. Use of Specified Span to Depth Ratio Limitations: Project 2009-04

High performance steel (HPS) are more durable and stronger, thus, it will result in designs that are more flexible / economical. However, the serviceability requirements on deflection can control the design of such sections due to their flexibility. This is a flaw in existing serviceability criterion that negates applications of HPS. The criterion is almost a century old and does not appear to be based on rational and/or scientific principles. This study through a comprehensive parameter study using finite element method, proposes changes to existing NJDOT Design Manual; and more importantly provides a more rational serviceability criterion that ensures human safety while allowing for application of HPS.

Background

Over the past couple decades there have been significant developments in availability of new materials and technologies suitable for civil infrastructure such as highway bridges. High performance steel (HPS) is one such a material that due to its unique alloy blend offers higher yield strength, enhanced weldability, weathering capabilities, and improved fracture toughness. As a result of higher strength it can result in lighter and much more economical designs. Furthermore, due to shallower girder depth, HPS can alleviate clearance requirement that is often critical, especially in urban areas. However, live-load deflection and span-to-depth (L/D) limitations of bridge design specifications negate the economical implementation of HPS.

AASHTO Standard Specifications limit live load service deflection to L/800 for general bridges and to L/1000 for bridges that are used by pedestrians. These limits were originally (almost a century old) employed presumably to avoid “undesirable structural or psychological effects due to their deformations." However, results of many studies indelicate that deflection and L/D limits do not necessarily address these objectives. It is as a result of such studies that AASHTO LRFD Bridge Specifications has now made these limitations optional; thus, transferring the responsibility for deflection control and serviceability requirements to the engineer and owner. Its commentary states that:

> *"These provisions permit, but do not encourage, the use of past practice for deflection control."*

It further states that

> *"Despite this, many owners and designers have found comfort in the past requirements to limit the overall stiffness of bridges. Their desire for the continued availability of some guidance in this area, often stated during the development of these specifications, have resulted in the retention of optional criteria, …"*

Thus, the purpose of this study is to shed additional light on suitability of existing serviceability requirements and to provide recommendations on criteria that ensure human safety and structural durability while allowing for economical use of high performance steel.

Research Objectives and Approach

WHY DEFLECTION LIMIT IMPACTS APPLICATIONS OF HPS?

Through a simple example it is demonstrated why the deflection limit can negate the application of high performance steel to highway bridges. Consider a simply supported beam loaded with a concentrated load at the center. The maximum moment, M_{max}, which is equal to PL/4, is used in strength-based design to size the member cross-section. That is, using the flexural equation stress-load relation is as follow:

$$\sigma = \frac{Mc}{I} = \frac{\frac{PL}{4}c}{I} = \frac{PLc}{4I}$$

In this equation, ***c*** is distance to extreme bending fiber and **I** is moment of inertia. In typical designs the above equation is solved for required moment of inertia to determine the section geometry. Subsequently, deflection is determined based on the following equation and checked against codes limits.

$$\Delta_{\max} = \frac{PL^3}{48EI}$$

For most cases the deflection limits are easily satisfied, often with a large margin. However, as discussed before existing deflection limits negates economical use of high performance materials because the original basis for these limits were not well established; and they did not consider existing bridge systems and the range of materials currently available.

To better see deflection-strength relation re-consider the flexural equation where the required moment of inertia, I_{req}, is determined based on material strength ($\sigma = \sigma_Y$):

$$I_{req} = \frac{PLc}{4\sigma_Y}$$

As it can be seen the higher the material strength the lower will be the required moment of inertia. The required moment of inertia considering deflection limit ($\Delta_{max}=\Delta_{lim}$):

$$I_{req} = \frac{PL^3}{48E\Delta_{\lim}}$$

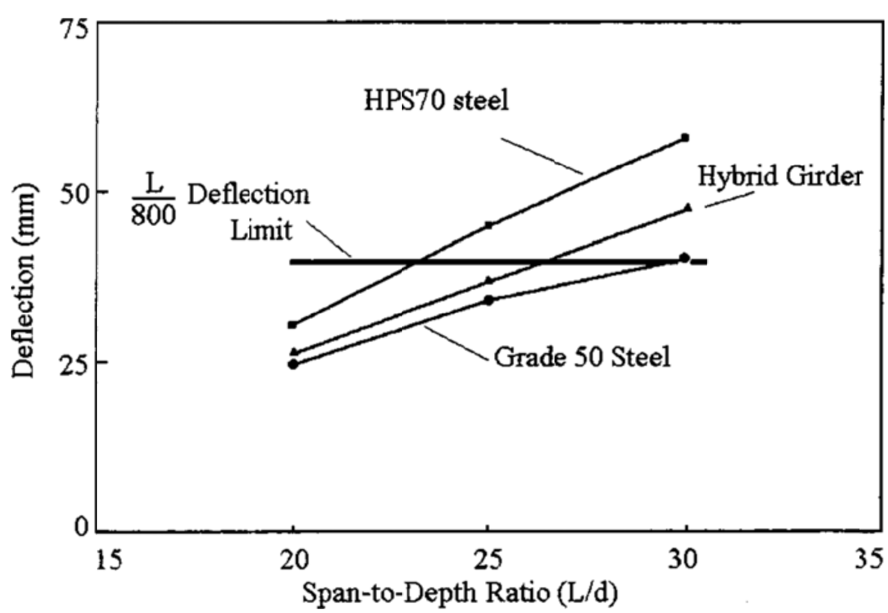
Where the smaller the deflection limit the higher is the required moment of inertia. Now if I is eliminated from he two equation one can drive the relationship between deflection limit and material strength as follow:

$$\Delta_{\lim} = \frac{1}{12E}\frac{L^2}{c}\sigma_Y$$

As it can be seen the higher the material strength the lower is the deflection limit, i.e., more stringent requirement. The span=to-depth ration vs. deflection graph highlights this point. As it can be seen from above discussions and this figure, the span-to-deflection, L/Δ, limit has significant impact on the use of high strength steel. Thus, the need for this timely study as defined and outlined in the next sections. This is a flaw in existing design specifications that rather penalizes the use of high strength material. Rational design methods will ensure that higher performance materials are used while structural serviceability and durability are achieved.

HAVE OTHERS LOOKED INTO THIS PROBLEM?

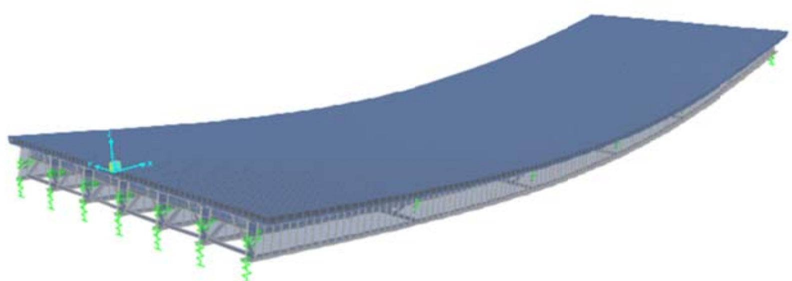
As it was mentioned AASHTO serviceability requirements dates back to almost a century ago. Naturally there have been a significant number of studies on this subject that is documented under the literature review section of the final report. The uniqueness of this study is multifold, namely; i) review of NJDOT design manual vis-à-vis



serviceability requirements as despite the fact that AASHTO has made these requirements optional, they are used by NJDOT, ii) Appropriateness of the listed span-to-depth ratios and to establish ratio limitations that address the use of higher structural steel grades, and iii) most importantly propose the "next generation" serviceability requirements that ensures human safety and structural performance while facilitating applications of high performance materials.

RESEARCH APPROACH

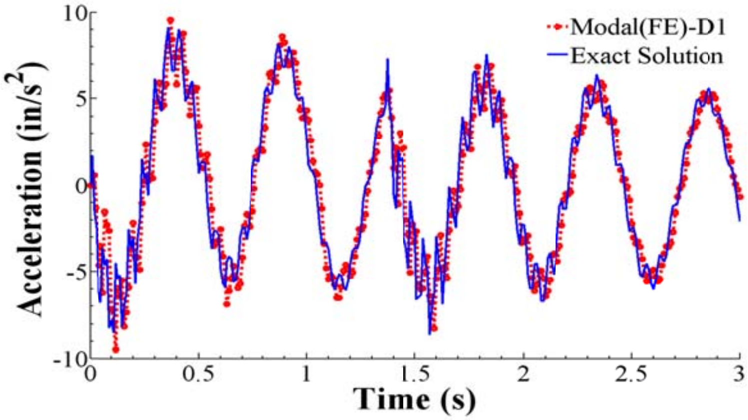
In light of the availability of other work on the subject including a comprehensive sponsored by NCHRP and completed in 2001, the initial phase of this study consisted of collecting and critically reviewing the existing work. It was clear from the review of existing work that there is a need for development of the "next generation" serviceability requirements. Thus, the next phase of the research included development of a reliable and effective finite element model to be used in an extensive parameter study.



The finite element parameter study included both 2-D and 3-D models. Among the parameters studied are: truck speed, span length, bridge frequency, speed and k parameters (related to previous three factors and the most critical to bridge vibration), damping ratio, number of axles, truck to axle length ratio, number of spans, spatial effect (3-D effect), bracing, and the boundary conditions. Although not

specifically among the initial tasks a limited field measurements was also conducted. These were two bridges on I-80E over I-287N and the Smith Road. The former is a steel bridge while the other is a reinforced concrete bridge. Both bridges have similar structural stiffness and satisfy AASHTO deflection requirements. However, their dynamic responses are significantly different highlighting the importance of other parameters to bridge dynamic response.

Although not within the scope of this technical brief to elaborate, but it must be mentioned that numerical simulation of bridge acceleration is quite sensitive to numerical assumptions and it is something that has not been investigated in prior work.



Almost all of the prior works on this subject were concerned with only the bridge displacement. However, it was determined that a truly rational serviceability requirement will need to include all important characteristics of bridge dynamic response including acceleration and frequency. Therefore, great effort was devoted to enduring accurate modeling of bridge acceleration under various loading conditions. This task of the project included comparison to exact solutions where available.

The study also included several case studies.

Findings

Based on the results of this research investigation two sets of recommendations are proposed. These are classified into short term (or incremental) and long term (or transformational). The former are changes that can easily be adopted within existing design manual and it is the determination of this study that they should be. While the latter is of transformational nature and might require review of other states as well as appropriate technical AASHTO committees. However, it is the determination of this study that this is the direction where the design specifications must go to ensure human safety, structural durability while allowing for applications of high performance material. To this end, NJDOT can take the lead in adopting the proposed serviceability requirement on a trial basis.

Short Term (incremental changes)

- Use L/800 not L/1000 as the deflection limit
  - May want to even consider further increase to L/450
- Do not use L/D limit(s)
  - This is more a clarification notice to engineers as NJDOT design manual does not require its use. However, since it is listed the designers tend to use it. This can be remedied by removing the article and providing the L/D ratios as an appendix to simply assist engineers during the initial design phase. The same can be used for HPS in estimating the initial depth.
- Do not use permit load for deflection criteria

    - This again might be an issue of clarity in language so that designers do not over conservatively interpret the manual as requiring the use of permit load.
- If permit load is used consider the following:
    - Impact factor is lower (essentially unity)
    - Not all lanes are loaded.
- Do not use moment distribution factor (DF) for deflection calculations. NJDOT manual correctly does not state its use. However, it does not clearly state that the deflection DF must be used. Therefore, designers tend to conservatively use the moment DF for deflection control.

- Do not use live load (LL) factor for deflection calculations. NJDOT design manual does not clearly state that Service I should be used for deflection control it just states the general load type of service limit state. It must be made more specific that Service I to be used in checking serviceability criteria.

Long Term (transformational changes)

- Use acceleration in establishing the serviceability requirement as follow:

$$\delta_{st} < \frac{A_{limit}}{1.2\alpha\omega^2}$$

- Use 100 in/sec^2 as the acceleration limit
    - This is based on Wright and Walker and can benefit from additional work on human factor vs. bridge dynamic response
- Use the above equation for speed parameter (α) less than 0.35, which includes most typical highway bridges.
    - For other values use the modified equation as presented in the report (as simple)
- The following is a simple application using Wright and Walker acceleration limit and 65 mph truck speed (note that - V/2LF where V is truck speed, L is bridge length and f is bridge frequency):

$$\delta_{st} < \frac{A_{limit}.}{1.2\ \alpha\ \omega^2} = \frac{A_{limit}.\,2Lf}{1.2\ V\ (2\pi f)^2} = \frac{100\ \left(\frac{in}{sec^2}\right) * 2 * L}{1.2 * 1144\left(\frac{in}{sec}\right) * 4 * \pi^2 * f}$$
$$= \frac{L}{270f}$$

- Observations on proposed criterion (its improvement over existing approach):
  - It is more rational by relating the deflection limit to other important bridge dynamic factors and truck speed.
  - For acceleration limit of 100 and typical bridge frequency of 3 Hz it is consistent with existing requirement of L/1000
  - It does not penalize high performance steel as acceleration limit is rationally related to the bridge flexibility.
  - For bridges with higher frequencies, since the vibration duration is lower it is not significantly noticeable. Therefore, the limits may be neglected for bridges with higher frequencies (e.g. f > 5).

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A final report is available online at http://www.state.nj.us/transportation/research/research.html

If you would like a copy of the full report, please FAX the NJDOT, Division of Research and Technology, Technology Transfer Group at (609) 530-3722 or send an e-mail to Research.Division@dot.state.nj.us and ask for:

Report Title: Design for Deflection Control vs. Use of Specified Span to Depth Ratio Limitations Project 2009-04.

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