Integration of Information and Automation Technologies in Bridge Engineering and Management: Extending State of the Art

ReSubmission Date:
May 11, 2006

Words: 7471

Authors:

Stuart S. Chen, Ph.D.,P.E.
Dept. of Civil Engrg., Univ. at Buffalo
226 Ketter Hall
Buffalo, New York 14260
Tel: (716) 645-2114 ext. 2428
Fax: (716) 645-3733
Email: ciechen@buffalo.edu

Arun M. Shirole', P.E.
Arora and Associates, P.C.
4527 Robin Circle
Robbinsdale, MN 55422
Tel: (763) 537-7073
Fax: (763) 537-0018
Email: ashirole@arorapc.com

ABSTRACT

Current U.S. practice of information transfer during the bridge design/ fabrication/ construction/ operation processes is fragmented. These processes involve repeated manual transcription of data which is error-prone, approvals (e.g., of shop drawings) which are time-consuming, and formats that beg for standardization to facilitate electronic information transfer. Without such standards, electronic information exchange is impossible. This paper surveys the shortcomings of current piecemeal applications of information and automation technologies. It then explores the promise of parametric 3D bridge information modeling (BIM) as an enabling technology for accelerating the design and delivery of bridges and articulates aspects of the envisioned accelerated bridge delivery process, to provide a glimpse of current technologies that are available to streamline the process of bridge delivery, and to articulate anticipated advances in the future that can be expected to facilitate accelerated bridge delivery.

In lieu of a complete industry-wide modeling of bridge information in a standardized format, savvy bridge design/build teams can be expected to attain competitive advantage by integrating computer-aided design (CAD), computer-aided engineering (CAE), and computer-integrated manufacturing (CIM) that will result in rapid and better quality project delivery and subsequent cost-effective life-cycle management. As a result, all three fundamental objectives of bridge delivery would be expected to be attained: higher quality, faster delivery, and more economical cost.

INTRODUCTION

We are nearing the end of an era. Bridge Engineering and construction have relied on drawings on paper as the primary representation of construction documentation for centuries. But we are essentially the only industry making 3D products without having at its core a digital product model representation and the streamlined product delivery that comes from the electronic data exchange capabilities facilitated thereby. Other closely related industries have documented and/or projected reduced costs, faster delivery, and improved quality as a result of implementing 3D CAD based integrated design and manufacturing processes along with accompanying interoperability standards, e.g., *(1) – (4)*. We in the bridge enterprise are overdue to do the same *(5)*. Failure to do so has been documented as a major cost center in the closely related capital facilities industry *(6)*.

Other recent and current efforts to represent and/or utilize electronic and/or 3D bridge data for various purposes omit major aspects of the overall design-through-construction process and thereby fail to leverage that data to anywhere near the extent possible. For example,

- Recent parametric design tools and transXML*(7)* omit such aspects as detailing for fabrication, construction management, erection procedures, etc.
- Recent software specifications and tools for the precast concrete industry *(8, 9)* are developing significant pieces of the 3D parametric modeling infrastructure needed for streamlined precast concrete components but to date are not oriented to the bridge industry.
- On the bridge-specific data modeling area, only limited aspects of the overall picture are addressed in any given research or deployment application, e.g., inspection *(10, 11)* - thus requiring manual entry of the data just for inspection, or design and rating *(12)* – similarly not leveraged for inspection or other aspects of asset management that such data could support, such as life-cycle costing *(13)*.
- 3D has been and is being used for visualization purposes (e.g., *(14, 15)*, see also various case studies assembled by the TRB Visualization Task Force *(16)*), but the same geometry painstakingly created merely for visualization is not leveraged for use in fabrication in construction.
- 3D has also been used for structural analysis of bridges too complex for their behavior to be predicted well enough by the traditional line-girder analyses (e.g., *(17)*), and for documenting as-built 3D geometries (e.g., *(18), (19)*). But such models are typically each standalone, once again not leveraging the use of 3D geometric bridge data for the multiple purposes it could serve due to the absence of electronic data exchange and interoperability standards for bridge data.
- Even when electronic data exchange is pursued (e.g., *(20)*), only relatively small pieces of the overall workflow involved in bridge delivery are addressed. Inefficiencies in the overall workflow process that could be eliminated by a full comprehensive re-engineering of the business processes to take full advantage of the 3D Bridge Information Modeling (BIM) are, consequently, therefore not addressed.

Thus, current U.S. practice of information transfer during the bridge planning/ design/ fabrication/ construction/ operation processes is fragmented. These processes involve repeated manual transcription of data which is error-prone, approvals (e.g., of shop drawings) which are time-consuming, and formats that beg for standardization to facilitate electronic information transfer. Without such standards, electronic information exchange is impossible. The purpose of this paper is to explore the promise of parametric 3D bridge information modeling (BIM) as an enabling technology for accelerating the design and delivery of bridges and to articulate aspects of the envisioned accelerated bridge delivery process, to provide a glimpse of current technologies that are available to streamline the process of bridge delivery, and to articulate anticipated advances in the future that can be expected to facilitate accelerated bridge delivery.

There are two distinct but related aspects of a streamlined approach:

- A single centralized 3D bridge data model or repository of the evolving bridge design, and
- Electronic data exchange standards that enable bridge design/ detailing/ fabrication/ erection/ management software applications to "talk to each other" so that tedious time-consuming error-prone manual data re-entry can be avoided.

The present paper focuses primarily on the first of these. As for the future, a complete modeling of bridge information in a standardized format (which does not yet exist) can be anticipated to facilitate integration of computer-aided design (CAD), computer-aided engineering (CAE), and computer-integrated manufacturing (CIM) that will result in rapid and better quality project delivery and subsequent cost-effective life-cycle management. As a result, all three fundamental objectives of bridge delivery would be expected to be attained: higher quality, faster delivery, and more economical cost.

CENTRALIZED MODEL CONCEPT

Figure 1 depicts the 3D model-centric vision for the integrated design and construction process, taken from a precast concrete presentation *(8)*. Similar diagrams appear for steel bridges in *(21)* and for capital construction projects in *(22)*. From the single central 3D model can be extracted only the current project information relevant to a given project stakeholder (e.g., owner, designer, contractor, fabricator, precaster, erector) at any given time. ***No more chasing down information from 2D drawings only to wonder whether it is current.***

2D vs. 3D

3D BIM (Bridge Information Modeling) processes for integrated design and construction have not previously been deployed for real bridge projects in the United States. CAD software packages used in the bridge industry routinely produce only traditional 2D drawings. 3D-based project documentation processes, however, are radically different than the traditional 2D-based processes, as summarized in Table 1 (adapted from *(8)*).

While it is true that 3D – centric processes have been deployed in other industries (e.g., aerospace and automotive), the CAD software packages that are available for those other industries do not currently provide a number of the features and amenities that would be desired by bridge industry stakeholders. These include, e.g., different loads and load combinations and analysis methods, complex roadway geometries using the terminology of highway and bridge engineers, and the multiple deflected geometries to be anticipated during the erection process for steel superstructures. These kinds of concerns do not outright prevent their application to bridges, but they make such application nontrivial. Figure 2 illustrates the aspects of a bridge-specific 3D-centric workflow explored in the work reported herein. The ideals of single data entry and of "model it, don't draft it" are followed as closely as possible throughout. Selected snapshots from this workflow are provided in the remainder of this paper.

An example of a partially constructed 3D model produced from available software is shown in Fig. 3. From this model can be extracted not only geometric data but also, e.g.,

- up-to-date shop drawings,
- quantity takeoffs and bills of materials,
- CNC (computer – numerically – controlled) input files to drive automated shop equipment such as rebar benders or beam-line hole – punching machines for steel members,
- piece-marking for coordination with shipping schedules, bills-of-lading and erector progress on-site,
- fabrication labor and material estimating, material procurement, and material management in the shop during fabrication,
- erection procedures, and
- bridge data used subsequently in rating calculations and various bridge management (asset management) functions.

Other references describing background for this work include references *(22 – 25)*.

ASPECTS OF INTEGRATED DESIGN-THROUGH CONSTRUCTION WORKFLOW

In this section we present a glimpse of what the implemented vision might look like to a user of integrated software that could be developed. This scenario makes use of existing technologies from distinct industries and adapts them for the bridge industry. Refer to Fig. 2 for a frame of reference in which to place the individual aspects illustrated subsequently herein.

In this scenario, the designer uses appropriate 3D modeling software to document the bridge design in 3D. Figs. 4 and 5 illustrate the bridge definition on the highway alignment and the resulting 3D model of the steel framing, respectively.

Once the designer creates the model, he exports it in a suitably exchangeable form (e.g., XML). This XML could be some blend of emerging dialects like transXML *(7)*, or future XML developments which will support robust data transfer for the bridge. The project web site would be enabled with effective XML visualization tools which will read the XML file uploaded by the designer and display it in 3D form. Once the designer uploads the drawings, the fabricator would log into his section of the website and can review the drawings in the fabricator's section of the project website. The fabricator would be able to inspect the 3D model of the design uploaded by the designer. In addition, he will have the option to view the XML and append fabrication attributes to it. The model could then be transferred via XML to detailing software (as indicated in the workflow, Fig. 2) to add information needed for full support of fabrication operations and shop drawing generation (if any stakeholders still think they need traditional 2D drawings). An example of such a model being detailed is shown in Fig. 6, encompassing detail down to the bolts and welds.

Thus, the central model would get updated, while always maintaining its complete integrity as the project progresses. Information in it would thus reliably be leveraged to drive downstream processes rather than relying on tedious time-consuming error-prone manual data re-entry to feed those downstream processes. This is not to say that independent checkpoints are removed – quite to the contrary! The checkpoints must obviously be kept in the new workflow while removing the possibility of infusing new errors through manual transcription.

The Fabricator's CAM system, which would be connected to the Internet, would have software translators to read the bridgeXML file and generate the G codes for the CNC machines. Shop drawings could also be generated from the same central bridgeXML file (although it is questionable whether there would in fact be any need for human-viewable 2-D shop drawings since we now have the 3-D central model and would be driving the CNC fabrication machines directly from that model).

The 3D centralized model, updated to as-fabricated geometry, could then be used to conduct virtual assembly. Being able to do this would shorten delivery schedules dramatically and reduce costs since physical pre-assembly (to ensure fit-up) would no longer be necessary. The model also would help the erector to visualize the assembly well before the erection starts. He could then anticipate the on-site problems and plan the erection process accordingly. Fig. 7 shows a portion of the 3D model showing diaphragm-to-girder connections of interest to the erector in this regard.

Features of such 3D modeling and detailing software typically include the following:

- Useful modeling tools, such as 3D grids, adjustable work area, and interference checking,
- A catalog of available material grades, profiles, and connection detailing utilities down to individual stirrup bends and individual bolts,
- Macros to assemble complex connections, subassemblies and indeed entire structures, such as trusses,
- Intelligent connections, such as end plates and clip angles, to automatically connect main members,
- Rebar detailing and material report generation,
- Links to transfer data to and from other software used for analysis, design, shop material management, and project scheduling and deliveries, and
- Drawing wizards to create drawings quickly and export data needed to drive CNC fabricating machines.

Steel detailing is not the only kind of detailing supported; reinforced concrete detailing can be supported as well. For example, Figs. 8 and 9 illustrate pier and deck rebar detailing, respectively. Table 2 tallies a detailed unit-cost based estimate where the quantities are all extracted automatically from the 3D model. Thus, the principal advantage of utilizing a 3D modeling approach stems from the reusability of the design data during tasks (e.g., material procurement, fabrication, etc.) that occur ***downstream*** from the initial design.

Manufacturing support software already provides the following kinds of capabilities to support streamlined operations:

- Centralized project details,
- Basic task management such as estimating, advanced bill of material preparation, purchase ordering, material checkout, stock keeping,
- Change order tracking, e.g., date change order arrived, date price was quoted, approval of price by general contractor,
- Communications log, e.g., phone conversation log with owner on a diaphragm clash issue,

- Two-way links to project scheduling software, to generate or update project schedules automatically,
- Integrated drawing viewer allowing e-redlining,
- CAD imports with revision control,
- Efficient material nestings, both from rolled steel and plate stock
- Automated purchasing integrated with self-maintaining inventory,
- Production tracking, e.g., complete shop floor time control for each process (drilling, handling, welding, blasting etc.,) so that more refined estimation and cost control can be done for future use.
- Automated shipping, e.g., auto generated shipping label for site receipt and verification.

ENVISIONED PAYOFFS

Engineers in related industries have reported the following kinds of productivity gains:

- Effective visualization of design alternatives, permitting a broader exploration of design alternatives early-on,
- Automatic drawing production (drawings are just reports extracted from model), e.g., 50 drawings @ 2 days/drawing vs. 1 model @ 12 days (100 days vs. 12 days) with drawings automatically extracted from the model *(26)*,
- Automatic quantity (Bill of Materials) generation, leading to quicker estimates
- Design changes are automatically updated (in other drawing sheets, sections, elevations, and details)
- Bridge the gaps between analysis, design and production of construction documentation
- Reduced need for fabrication drawings
- 2.5 – 15% reduction in construction costs and 10 – 15% reduction in project schedule, a significant portion of which is from reduction in field rework (*(1) – (4)*).

GLIMPSE OF THE FUTURE

Although many individual pieces of the envisioned workflow described above are possible today with available software, there are still several key "missing links." The principal missing link is an industry standard bridge data modeling language that is sufficiently robust to support interoperability of bridge information for the entire bridge lifecycle. In order to achieve maximum benefit from management of bridge information as it evolves throughout its lifecycle starting from design, the authors believe that the following will be needed in order to leverage maximum benefit from 3D parametric Bridge Information Modeling:

- Endorse the extension of transXML (or development of bridgeXML) to support more comprehensive bridge data modeling to support all aspects of the bridge lifecycle; developing such will likely require forceful leadership by an agency that is strong enough to ensure broad stakeholder participation in a cause that is not guaranteed ahead of time to be "win-win" for all.
- Bridge owners need to conceive of themselves as owner-stewards of the bridge ***data*** as it evolves, not just as owner-stewards of the constructed bridge itself.
- A suite of projects should be run "model-centric" in parallel with conventional 2D approaches for producing design documentation and construction documents, using an

incremental phased approach to build a track record to document practices needed to attain "better, faster, more economical" bridge delivery based on BIM methodologies.

- "Model Management" QA/QC from the earliest stages is needed to support the information needs of downstream stakeholders, i.e., a genuine teamwork-based culture. Thus, model information must be sufficiently accurate not only to bid from, but also to build from.

XML- the *eXtensible Markup Language* -- has recently emerged as a new standard for data representation and exchange on the Internet. Leading software developers are committed to XML and are quickly moving towards using XML internally as well as creating XML-oriented tools and products. Since XML provides a standard syntax for representing data, it is perceived to be a key enabling technology for the digital exchange of information on the world-wide web (WWW). Design, construction, operation and maintenance of steel and concrete bridges have unique data transfer needs; thus there is a need for initiating XML schema development efforts to support integrated design and construction of these bridges. With such schema, independent stakeholders agree to use a common language (vocabulary) for interchanging data.

Even before implementing XML schema, however, it is desirable to develop a implementation- independent description of the domain. The Unified Modeling Language (UML) is emerging as the most popular representation scheme in standards development projects. Thus, prior to XML implementation, a series of UML diagrams would need to be developed to define the syntax (terminology), semantics (meaning), and constraints of stylized bridge design, construction, operation and maintenance vocabulary.

It is thus desirable to develop bridgeUML diagrams and corresponding bridgeXML schema along with demonstration examples to support web-friendly electronic data exchange for interoperability throughout the process of designing, constructing, erecting, and operating a steel or concrete bridge structure. This effort would be an attempt to integrate the entire bridge lifecycle around the notion of a single central 3D bridge "data warehouse" which is accessible (with suitable permission levels) to each of the stakeholders involved in the process of designing, constructing, and operating a bridge. The stages involved would need to include not only design and fabrication but also change tracking, inspection tracking, virtual assembly, construction, as-built documentation, and records management *(27)*.

IMPLICATIONS FOR PRACTICE

In order to bring about the advancements needed to move the bridge industry to accelerated delivery without increasing cost or sacrificing quality, it would appear that at least the following must occur:

- A complete modeling of bridge information in a standardized 3D digital format with accompanying commercial-strength bridge-friendly parametric 3D-capable software;
- Increasing use and acceptance of the D/B (design/build) mode of project delivery or at least the removal of disincentives to electronic information exchange that are inherent in conventional D/B/B (design/bid/build) project delivery;
- A re-thinking and resulting redefinition of the roles of the respective stakeholders involved in bridge delivery in accordance with the above two developments.

In addition, a collaborative industry-wide monitoring and shepherding of developments will be necessary, in line with the resolution recently passed in the 2005 AASHTO SCOBS Annual Meeting, which concludes with these words: "Be it Resolved: That the AASHTO Highway Subcommittee on Bridges and Structures acknowledges the importance of 'Comprehensive Integrated Bridge Project Delivery through Automation' in achieving its goals. Further Subcommittee affirms its leadership role by charging one of its existing Technical Committees or a separate Task Force to coordinate further development, refinement and transfer of this technology in partnership with the FHWA."

Each of these are discussed briefly with practitioner implications in the following.

Complete 3D Parametric Modeling in Standardized Digital Format

Although the advantages of 3D models vs. 2D drawings are clear (Table 1), making full use of these models requires that issues involving methods of data presentation and exchange through the internet or other electronic means be addressed. Such exchange requires major standards development, for which common languages need to be used to be of ultimate benefit to all involved in using these technologies. The initial step in this direction will be to develop an implementation-independent description of the domain that defines terminology (syntax), meaning (semantics), and constraints of bridge design, construction, operation and maintenance vocabulary. Design, construction, operation and maintenance of steel and concrete bridges have unique data presentation and transfer needs; thus, development efforts must be initiated to support integrated bridge design and construction. The emerging Unified Modeling Language (UML) and Extensible Markup Language (XML) are now available to address the needs of data presentation and digital exchange of information expeditiously.

While all that may appear daunting, a smoothly running team can pre-emptively develop their own team "bridge language" standard without having to wait for an entire industry to develop an industry-wide standard. Competitive advantage is to be gained by converting workflows to 3D BIM approaches sooner rather than later.

D/B Mindset vs. D/B/B Adversarial Fragmentation

"Who owns the model?" is a question that often arises among individual stakeholders who first hear about 3D BIM concepts, but are themselves still steeped in the current adversarial fragmented way of doing business in the construction industry in general and the bridge industry in particular. This question is presumably asked partly out of concern for liability (e.g., if errors in electronic data are carried forward into construction), and partly due to the conventional understanding of drawings as "instruments of service." The recently issued Appendix A "Digital Product Models" of AISC *(28)* addresses the second aspect of the issue in a common-sense way, e.g., that in the absence of ownership clauses to the contrary in the Contract Documents, information added to the model by the Fabricator belongs to the Fabricator (while information in the model provided by the designer is owned by the designer). Perhaps more to the point, however, is how Design/Build (D/B) projects can remove some of the business process fragmentation. Here there are increased incentives for the streamlined process that would result from sharing of electronic information among project stakeholders. It can be anticipated that savvy D/B teams will increasingly exploit the possibilities in this regard before Design/Bid/Build (D/B/B) projects will.

Re-Shaping of Stakeholder Roles

In the envisioned 3D BIM approach, the integrity of the model is paramount. As such, "it is imperative that an individual entity on the team be responsible for maintaining" the model in order to ensure data integrity and security and to coordinate flow of information to all team members when information is added to the model, and to assure proper tracking and control of revisions *(28)*. Whether this entity is the design engineer, the detailer, or a new "model manager" stakeholder, other stakeholders will likely have their own workflow impacted. For example, dimensions cannot be "fudged" on drawings since the drawings, no longer work products in their own right, now are reports extracted directly from the central model – a model which will be used, e.g., to generate CNC (Computer numerically controlled) data for use in fabrication operations. Thus, the dimension needs to be accurate enough not only to bid from but also to build from. The implications of this brave new world for each stakeholder are still to be understood in their full extent. Business model and "best practices" implications will need to be hammered out both regarding steel (e.g., *(29)*), and concrete (e.g., *(30)*).

SUMMARY

In the present paper, a future is envisioned for the accelerated delivery of bridges based on the following notions:

- A comprehensive information-centric approach to the planning, design, construction, operation and maintenance of bridges through a single coordinated shepherding of bridge information serving multiple purposes as it evolves, and
- A coordinated leveraging of design information into downstream operations: 3D visualization, detailing, "shop drawing" production & review, "erection drawing" production and review, CNC-driven fabrication, construction, operation & maintenance, asset management, health monitoring and condition assessment, etc.

The need is articulated for further bridge industry effort to hammer out a uniform language for electronic communication of bridge lifecycle information in order to shepherd such a vision into reality. Commercial-strength bridge-friendly parametric 3D-capable software, bridge owners friendly to, and supportive of, streamlined business practices, and stakeholders migrating toward 3D-BIM based collaborative ways of doing business are needed to transfer the results fully to highway practice.

ACKNOWLEDGMENTS

This work was sponsored by the American Association of State Highway and Transportation Officials, in cooperation with the Federal Highway Administration and Bentley Systems, and was conducted in the National Cooperative Highway Research Program Ideas Deserving Exploratory Analysis (NCHRP-IDEA), which is administered by the Transportation Research Board of the National Research Council. The opinions and conclusions expressed or implied in the report are those of the authors. They are not necessarily those of the

Transportation Research Board, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, or the individual states participating on the National Cooperative Highway Research Program. The contributions of the following current and former graduate students are significant and are gratefully acknowledged: Vamsi-Krishna Tangirala, Junwei Li, Nagarajan Kannan, Krishnakanth Potturi, and Rahul Patil.

REFERENCES

1. FIATECH Fully Integrated and Automated TECHnology "Capital Projects Technology Roadmap Initiative: Executive Summary," March 2003, http://www.fiatech.org/pdfs/projects/ExSummary.pdf (Accessed March 2004).

2. Khanzode, A., and Fischer, M., "Potential Savings from Standardized Electronic Information Exchange: A Case Study for the Steel Structure of a Medical Office Building," CIFE Technical Report #121, Center for Integrated Facility Engineering, Stanford University, July 2000. Available at http://www.stanford.edu/group/CIFE/online.publications/TR121.pdf (Accessed Nov. 2005).

3. Post, N. M., "Steel Sector Plans for Paradigm Shift." *enr.construction.com* (April 03 issue), http://enr.construction.com/news/buildings/archives/030414.asp (March 2004).

4. Sacks, E., "Evaluation of Economic Impact of Three-Dimensional Modeling in Precast Concrete Engineering," ASCE Journal of Computing in Civil Engineering, Vol. 18, No. 4, October 2004, pp. 301 – 312.

5. ___, "3D Modeling Has Come of Age, but the Industry is Lagging," Editorial in Engineering News Record, McGraw-Hill, July 2005, http://enr.ecnext.com/free-scripts/comsite2.pl?page=enr_document&article=opedar050711 (Accessed Nov. 2005).

6. Gallaher, M. P., O'Connor, A. C., Dettbarn, J. L., and L. T. Gilday, "Cost Analysis of Inadequate Inoperability in the Capital Facilities Industry," National Institute of Standards and Technology (NIST) Technical Report No. NIST GCR-04-867, August 2004, 210 pp., http://www.bfrl.nist.gov/oae/publications/gcrs/04867.pdf (Accessed Nov. 2005).

7. NCHRP 20-64 XML Schemas for the Exchange of Transportation Data, http://www.transxml.net/ (Accessed August 2005).

8. Sacks, R., "Can parametric 3-D computer-modeling prevent errors in Precast Construction?", PCI Convention, Nashville TN October 2002.

9. Sacks, R., Eastman, C. M., and Lee, G., "Parametric 3D Modeling in Building Construction with Examples from Precast Concrete," Automation in Construction 13(3), 2004, pp. 291-312.

10. Haque, M. E., and K. Pongponrat, "Integrated Multimedia Uniform Bridge Element Identification System Database for Bridge Inspection and Maintenance," Paper No. 00-0569, Transportation Research Record 1697, pp. 1 – 5, 2000.

11. Jauregui, D. V., and K. R. White, "Implementation of Virtual Reality in Routine Bridge Inspection," Paper No. 03-2300, Transportation Research Record 1827, pp. 29 – 35, 2003.

12. AASHTOWare, “Draft Opis/Virtis Application Program Interface Documentation,” August 2002.

13. Thompson, P. D., “Bridge Life-Cycle Costing in Integrated Environment of Design, Rating, and Management,” Transportation Research Record 1866, pp. 51 – 58, 2004

14. Wallsgrove, J., and R. Barlow, “Virtual Reality Images to Aid Public Involvement in Appearance of Roads and Bridges,” Paper No. 01-2754, Transportation Research Record 1770, pp. 166 – 172, 2001.

15. Hughes, R. G., “Visualization in Transportation: Current Practice and Future Directions,” Transportation Research Record 1899, pp. 167-174, 2004.

16. Transportation Research Board Visualization in Transportation Task Force, “Advancing the Research and Application of Visualization Technologies in Transportation,” http://trbvis.org (accessed Nov. 2005).

17. Norton, E. K., Linzell, D. G., and J. A. Laman, “Examination of Response of a Skewed Steel Bridge Superstructure During Deck Placement,” Paper No. 03-4119, Transportation Research Record 1845, pp. 66 – 75, 2003.

18. Bloomquist, D., “Acquisition of Laser-Based Data Measurement Systems,” Final Report BC-354 #87 to Florida Department of Transportation, May 2005, http://www.dot.state.fl.us/research-center/Completed_Proj/Summary_STR/FDOT_BC354_87_rpt.pdf (accessed Nov. 2005).

19. Shih, N. J., Wu, M. C., and J. Kunz, “The Inspections of As-Built Construction Records by 3D Point Clouds,” Working Paper WP-090, August 2004, Center for Integrated Facility Engineering, Stanford University, http://www.stanford.edu/group/CIFE/Publications/index.html (accessed Nov. 2005).

20. Steel Bridge Collaboration Task Force on Electronic Data Transfer, “Proposal for Steel Bridge Collaboration Standards for Electronic Data Transfer,” http://steelbridge.org/TG1/TG-1%20electronic-approval.pdf (accessed Nov. 2005).

21. Chen, S. S., N. Kannan, R. B. Patil, and K. Potturi, “Evaluation of 3D Computer Modeling and Electronic Information Transfer for Efficient Design and Construction of Steel Bridges,” Revised Draft Final Report on Project 20-7, Task 149, National Cooperative Highway Research Program (NCHRP), November 2003.

22. Vanegas, J. A., Pearce, A. R., Garrett, J., and O’Brien, W., “An Interdisciplinary Charette: Setting an Academic Research Agenda for the FIATECH Capital Projects Technology Roadmap Initiative,” December 2004, http://www.fiatech.org/pdfs/deliverables/Roadmap/v5.01Dec04Final_Report.pdf (accessed August 2005).

23. Tamai, S., Yagata, Y., and Hosoya, T., “New Technologies in Fabrication of Steel Bridges in Japan,” Journal of Constructional Steel Research, 58 (2002) pp. 151-192.

24. Verma. K., et al., "Steel Bridge Fabrication Technologies in Europe and Japan, Report No. FHWA-PL-01-018, http://www.international.fhwa.dot.gov/Pdfs/SteelBridge1.pdf (March 2001, Accessed Nov. 2005).

25. Chen, S. S., ed., "Computer Integrated Steel Bridge Design and Construction: Expanding Automation," Workshop Report to the Federal Highway Administration and National Steel Bridge Alliance, http://www.fhwa.dot.gov/bridge/automate.htm (April 2002, Accessed Nov. 2005).

26. McDowell, M., "Best Practices from a Structural Engineering Perspected," presented at BE (Bentley Empowered) International User Conference, Baltimore, MD, May 2005.

27. Shirole', A. M., "Bridge Management to the Year 2000 and Beyond," Transportation Research Board Conference on Bridge Management, Austin, Texas, September 1993.

28. American Institute of Steel Construction, Inc., "Code of Standard Practice for Steel Buildings and Bridges," March 18, 2005, http://www.aisc.org/ContentManagement/ContentDisplay.cfm?ContentID=27917 (accessed Nov. 2005).

29. Carrato, P., and M. Holland, "Business Practices in a 3D Structural Model Environment: How Do They Affect the Steel Designer and Detailer," ASCE Structures Congress, May 2004.

30. Sacks, E., Eastman, C. M., and G. Lee, "Process Model Perspectives on Management and Engineering Procedures in the Precast/Prestressed Concrete Industry," ASCE Journal of Construction Engineering and Management, Vol. 130, No. 2, March/April 2004, pp. 206-215.

LIST OF FIGURES

LIST OF TABLES

TABLE 1: 2D vs. 3D

2D CAD provides an Electronic "drawing board"	3D CAD enables a parametric model
2D Drawings contain the information	3D model contains the information; drawings are only reports
2D Drawings intended to be human-readable; separate manual data entry is required for analysis	3D model is computer-readable, such that direct analyses are possible
Coordination is difficult; information is scattered among different drawings and specifications clauses	Coordination is automatic: 3D model is the single source for all product information
Manual checking	Automated checking
No support for production	Potentially full support for production (via CNC codes etc.)

TABLE 2 Material Takeoff (Extracted Entirely From Model) and Estimate

Family	Component	Description	Weight Unit	Weight (Mass)	Quantity	Unit	Unit Price	Total
Deck	28 MPa deck concrete N	28 MPa concrete for N. bound bridge deck	kg	499.4	207.75	m3	$260.00	$54,015.00
Deck	28 MPa deck concrete S	28 MPa concrete for S. bound bridge deck	kg	499.4	207.75	m3	$260.00	$54,015.00
Deck	Lat Rebar N	transverse rebar for N. bound bridge deck	kg	8330.4	8330.4	kg	$1.50	$12,495.60
Deck	Lat Rebar S	transverse rebar for S. bound bridge deck	kg	8247.4	8247.4	kg	$1.50	$12,371.10
Deck	Lon Rebar N	Longitudinal rebar for N. bound bridge deck	kg	8249	8249	kg	$1.50	$12,373.50
Deck	Lon Rebar S	Longitudinal rebar for S. bound bridge deck	kg	8234.4	8234.4	kg	$1.50	$12,351.60
Deck	Shear Studs N	Shear studs for N. bound composite deck	kg	4608	5760	pc	$2.50	$14,400.00
Deck	Shear Studs S	Shear studs for S. bound composite deck	kg	4608	5760	pc	$2.50	$14,400.00
Foundation	Concrete N	28 MPa Concrete for N. abutments	kg	411.5	171.16	m3	$260.00	$44,501.60
Foundation	Concrete S	28 MPa Concrete for S. abutments	kg	406.8	169.2	m3	$260.00	$43,992.00
Foundation	HP 250 X 85 N	HP piles for N. abutment	kg	31905	350	m	$130.00	$45,500.00
Foundation	HP 250 X 85 S	HP piles for S. abutments	kg	31905	350	m	$130.00	$45,500.00
Parapet	Lat Rebar N	Transverse parapet rebar N. bound	kg	1795.4	1795.4	kg	$1.50	$2,693.10
Parapet	Lat Rebar S	Transverse parapet rebar S. bound	kg	1795.4	1795.4	kg	$1.50	$2,693.10
Parapet	Lon Rebar N	longitudinal parapet rebar N. bound	kg	1002.6	1002.6	kg	$1.50	$1,503.90
Parapet	Lon Rebar S	longitudinal parapet rebar S. bound	kg	1002.6	1002.6	kg	$1.50	$1,503.90
Superstructure	HPS Steel N	High performance weathering steel for plate girders N. bound	kg	191995.2	191995.2	kg	$3.00	$575,985.60
Superstructure	HPS Steel S	High performance weathering steel for plate girders S. bound	kg	191995.2	191995.2	kg	$3.00	$575,985.60
						Grand Total		$1,526,280.60

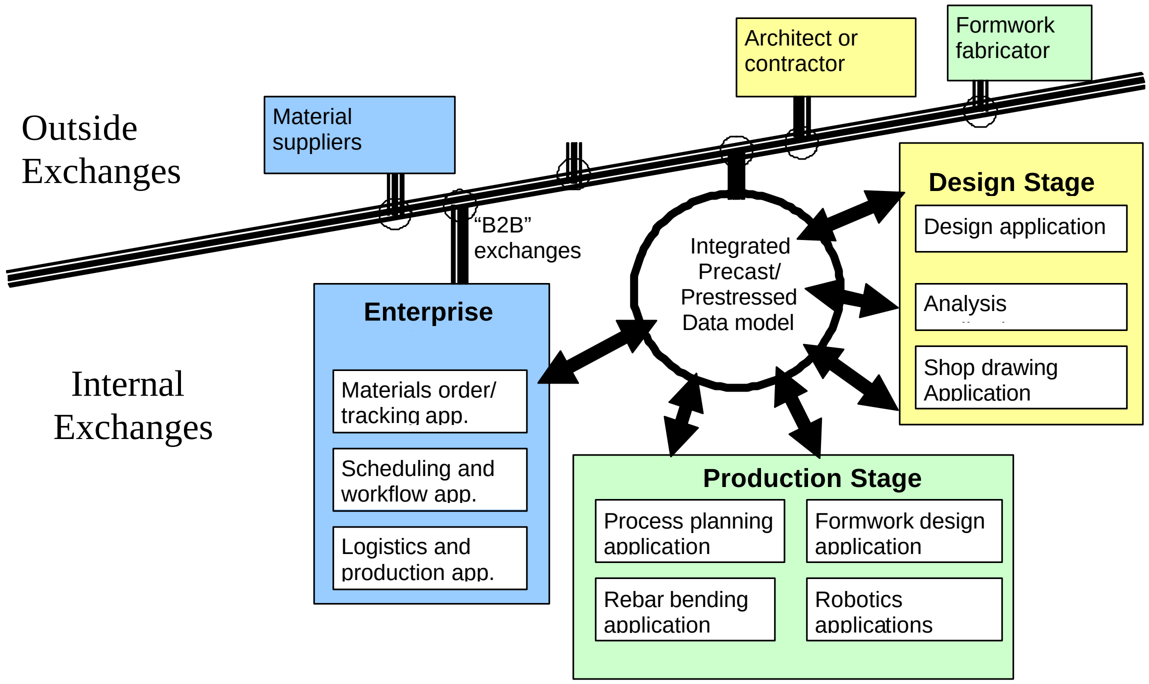

FIGURE 1 Centralized model supporting integrated process [8].

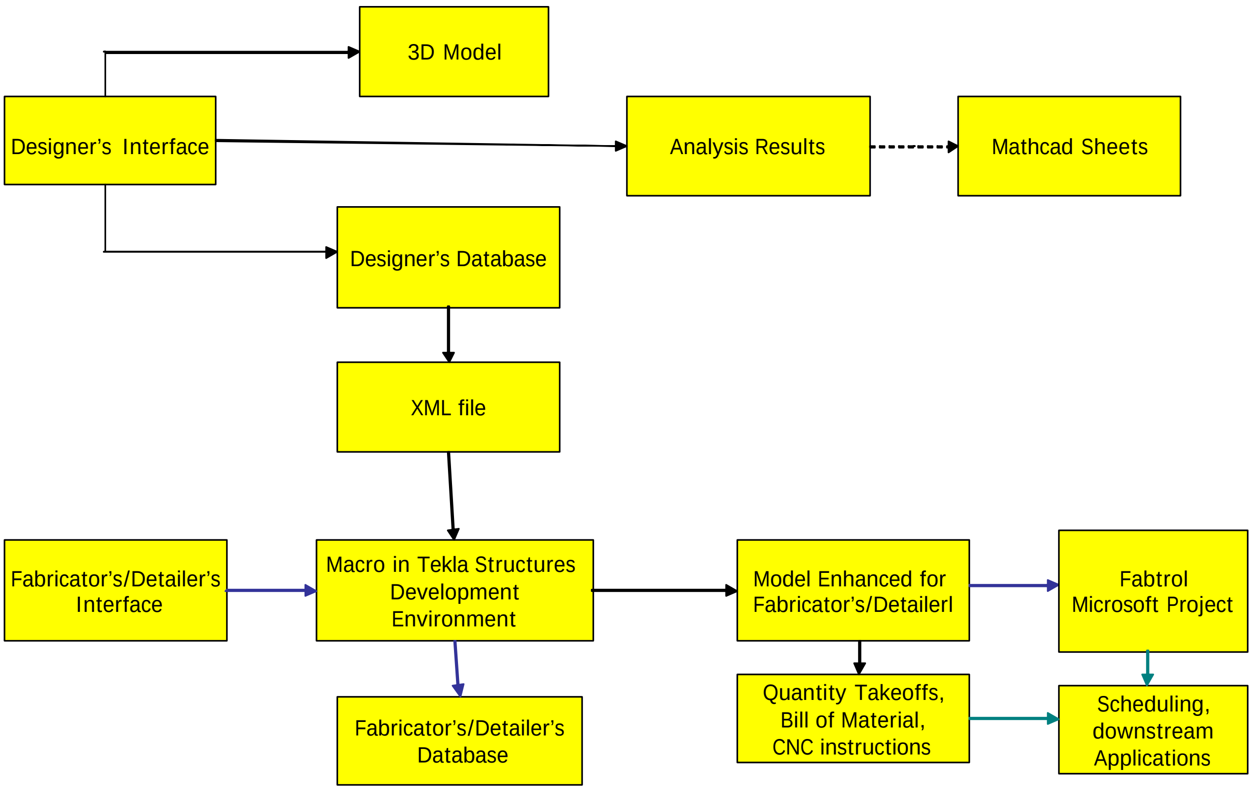

FIGURE 2 Workflow explored using 3D BIM (Bridge Information Model).

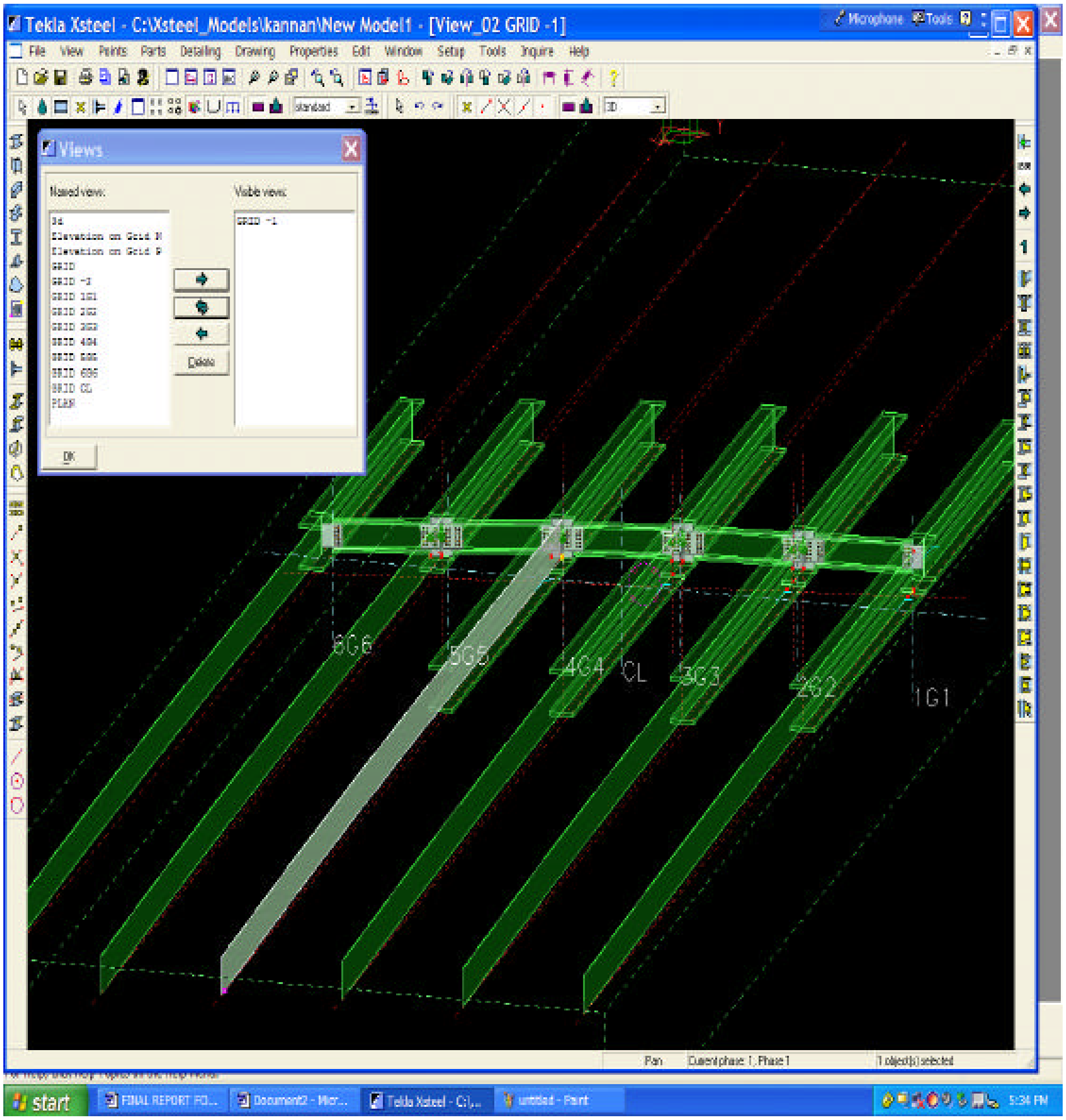

FIGURE 3 Partial 3D steel bridge model (girder portions and diaphragms using Tekla software) [21].

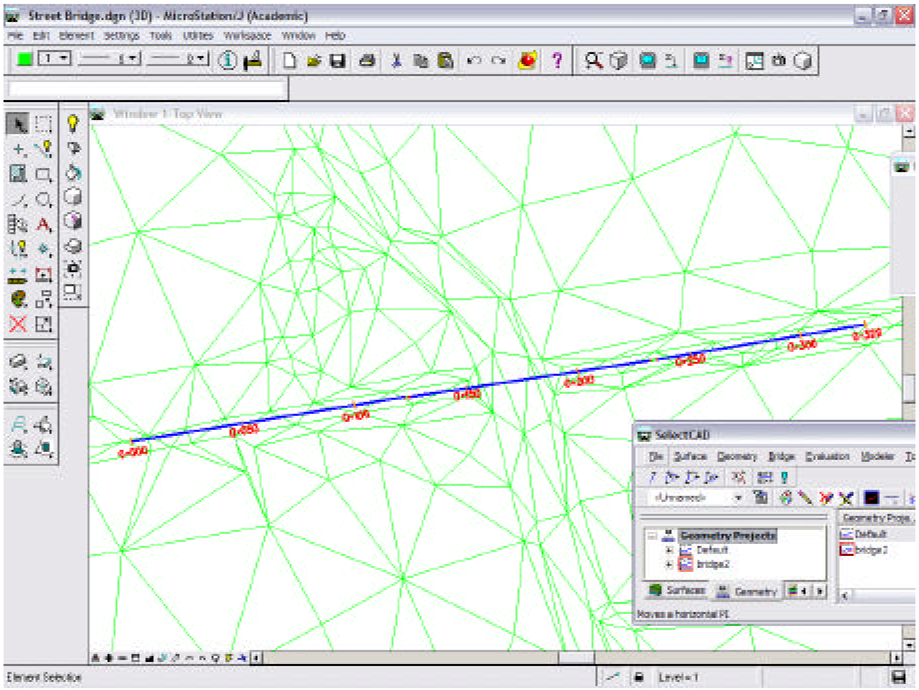

FIGURE 4 Bridge location on roadway alignment using Bentley software (www.bentley.com) [21]

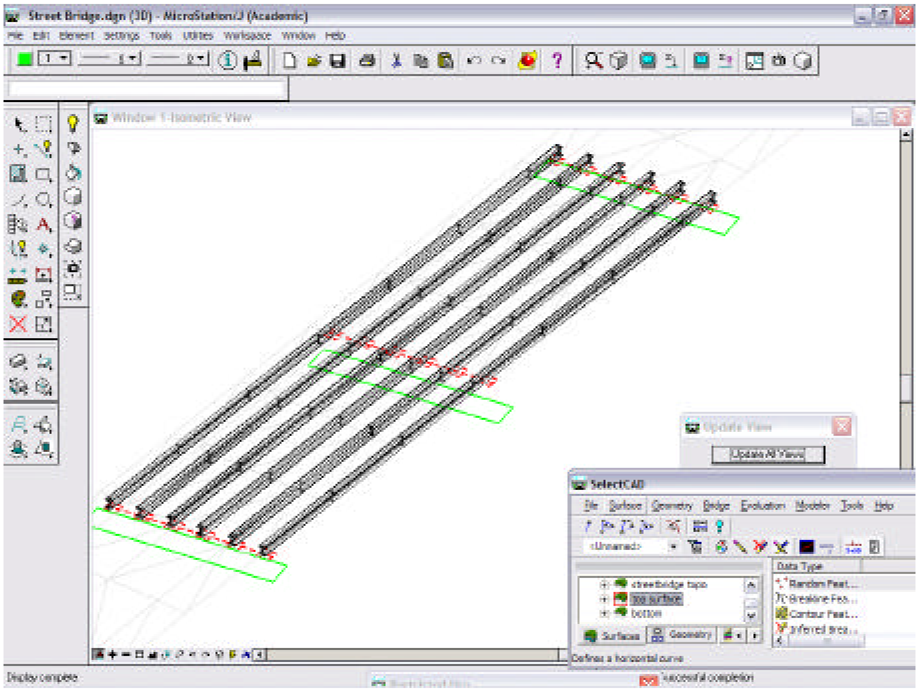

FIGURE 5 3D model of steel bridge framing using Bentley software (www.bentley.com) [3].

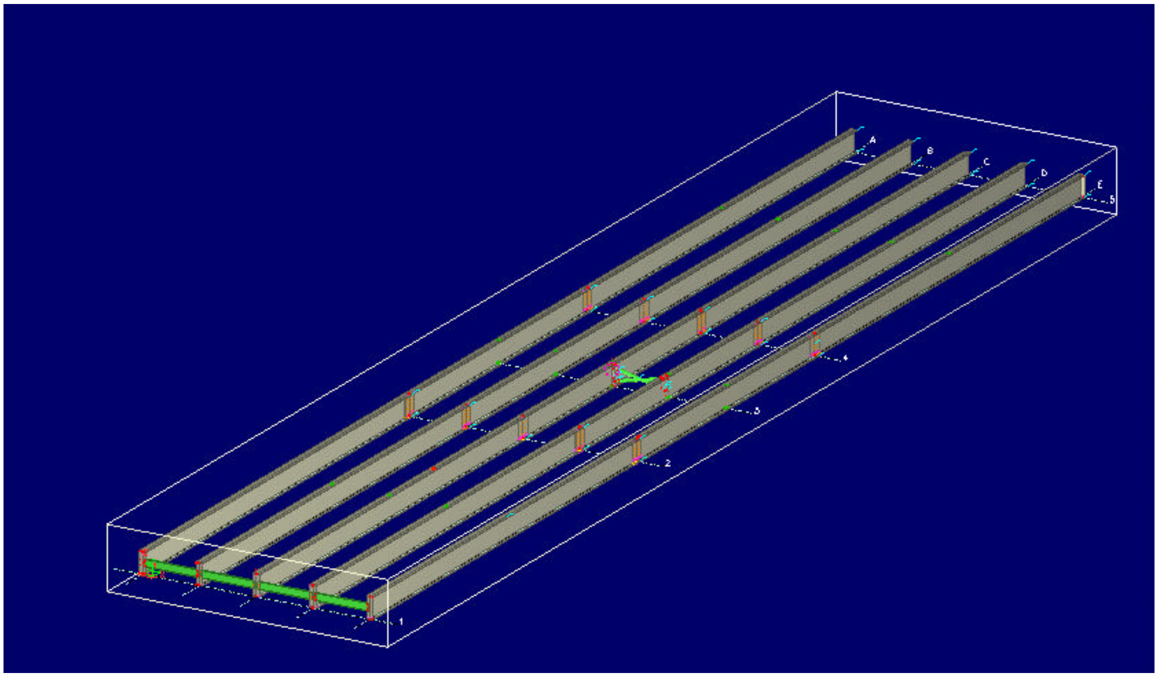

FIGURE 6 3D model under construction in detailing software (www.tekla.com).

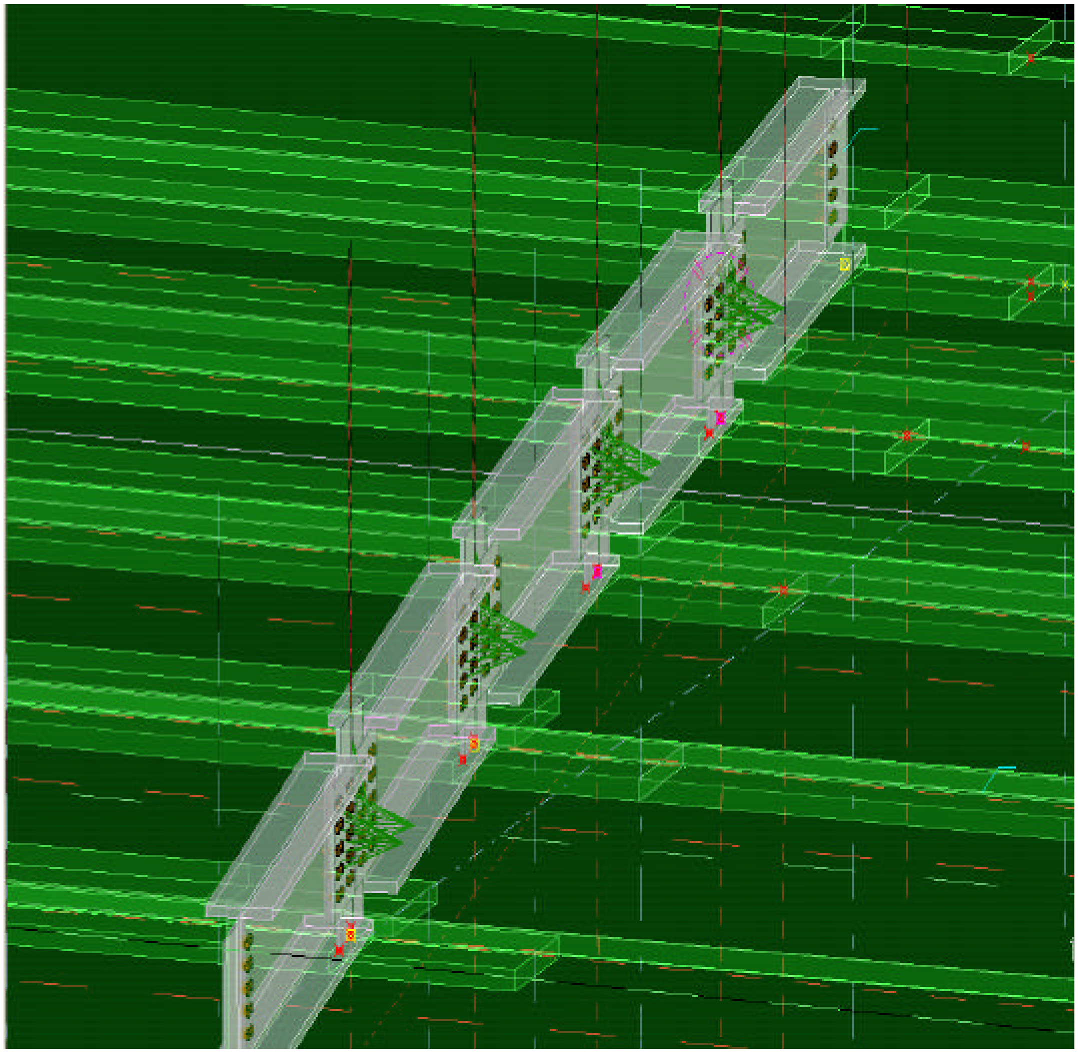

FIGURE 7 Diaphragm placement in 3D model using Tekla software (www.tekla.com).

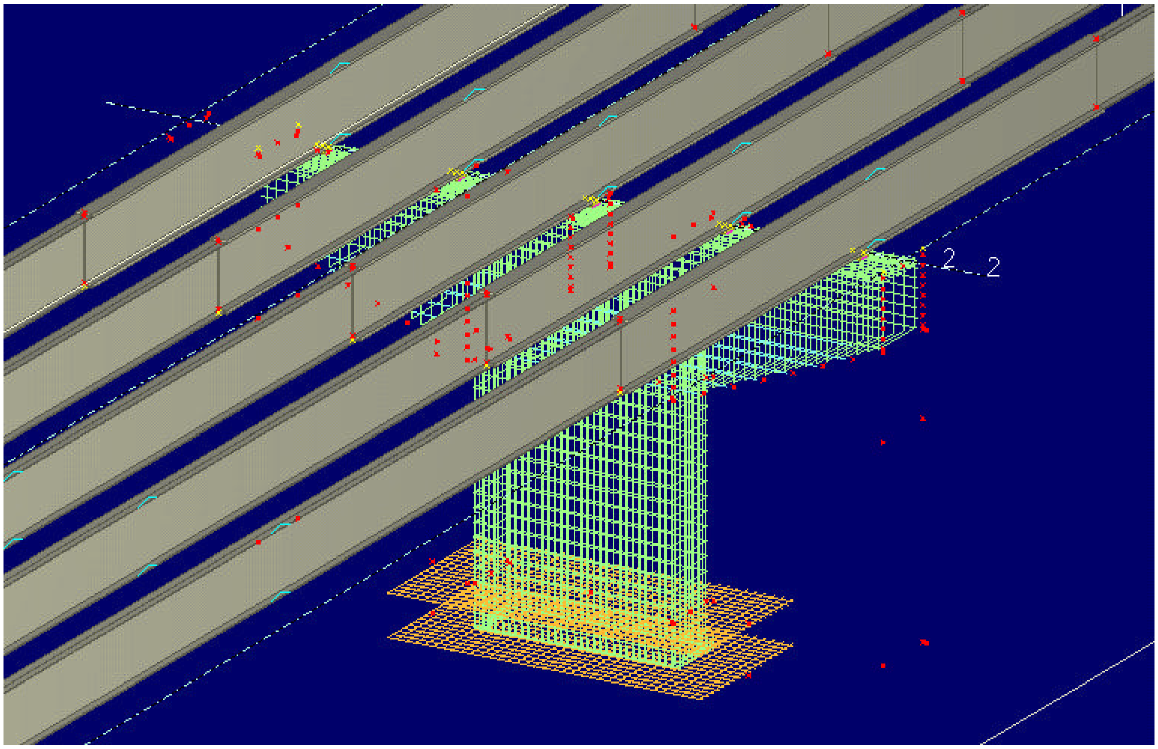

FIGURE 8 Pier detailing in 3D model using Tekla Structures (www.tekla.com).

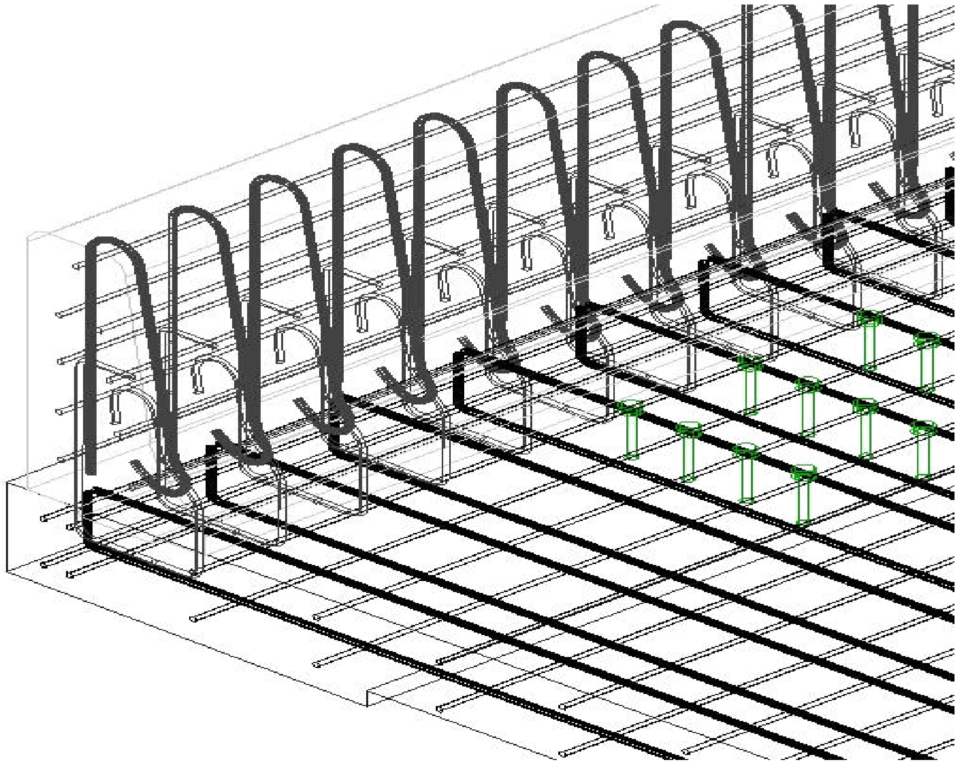

FIGURE 9 Deck detailing in 3D model using MicroStation TriForma (www.bentley.com).