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Accelerating the Design and Delivery of Bridges with 3D Bridge Information Modeling: Pilot Study of 3D-Centric Modeling Processes for Integrated Design and Construction of Highway Bridges

Final Report for Highway IDEA Project 108

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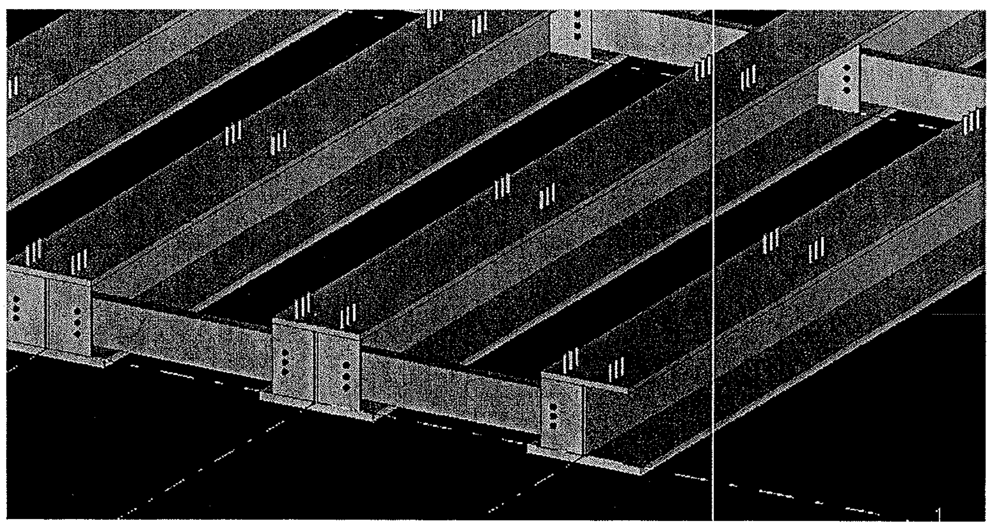
Pilot Study of 3D-Centric Modeling Processes for Integrated Design and Construction of Highway Bridges



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Accelerating the Design and Delivery of Bridges with 3D Bridge Information Modeling:
(NCHRP IDEA Project 108: Pilot Study of 3D-Centric Modeling Processes
for Integrated Design and Construction of Highway Bridges)

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Accelerating the Design and Delivery of Bridges With 3D Bridge Information Modeling

NCHRP 108 – Pilot Study of 3D-Centric Modeling Processes for Integrated Design and Construction of Highway Bridges

Revised Draft Final Report
August 2006

EXECUTIVE SUMMARY

This project addresses the development and implementation of 3D modeling (instead of 2D drafting) as a means of streamlining the delivery of highway bridges. 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 report first surveys the shortcomings of current piecemeal applications of information and automation technologies. It then explores the promise of parametric 3D bridge information modeling (BrIM) as an enabling technology for accelerating the design and delivery of bridges in the context of practical example bridge structures. These examples are used as a basis for articulating 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 would be expected and needed to fully transfer these nascent technologies into industry practice in order thereby 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.

1. BACKGROUND AND 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., [FIATECH 2004], [Khanzode and Fischer 2000], [Post 2003], [Sacks 2004]). We in the bridge enterprise are overdue to do the same [ENR 2005]. Failure to do so has been documented as a major cost center in the closely related capital facilities industry [Gallaher et al. 2004].

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[NCHRP 2005] omit such aspects as detailing for fabrication, construction management, erection procedures, etc.
- Recent software specifications and tools for the precast concrete industry ([Sacks 2002], [Sacks et al. 2004]) 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 ([Haque and Pongponrat 2000], [Jauregui and White 2003]) - thus requiring manual entry of the data just for inspection, or design and rating [AASHTOWare 2002] – similarly not leveraged for inspection or other aspects of asset management that such data could support, such as life-cycle costing [Thompson 2004].
- 3D has been and is being used for visualization purposes (e.g., [Wallsgrove and Barlow 2001], [Hughes 2004]), see also various case studies assembled by the TRB Visualization Task Force [TRB 2005]), 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., [Norton et al. 2003]), and for documenting as-built 3D geometries (e.g., [Bloomquist 2005], [Shih et al. 2004]). 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., [Steel Bridge 2005]), 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 (BrIM) 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 (BrIM) 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.

1.1 Centralized Model Concept

Figure 1 depicts the 3D model-centric vision for the integrated design and construction process, taken from a precast concrete presentation [Sacks 2002]. Similar diagrams appear for steel bridges in [Chen et al. 2003] and for capital construction projects in [Vanegas et al. 2004]. 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 BrIM (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 [Sacks 2002]).

Table 2 presents a complementary way of comparing current (status quo) processes with the possibilities presented by a coordinated bridge information modeling approach utilizing 3D modeling at its core.

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; 2D 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.)

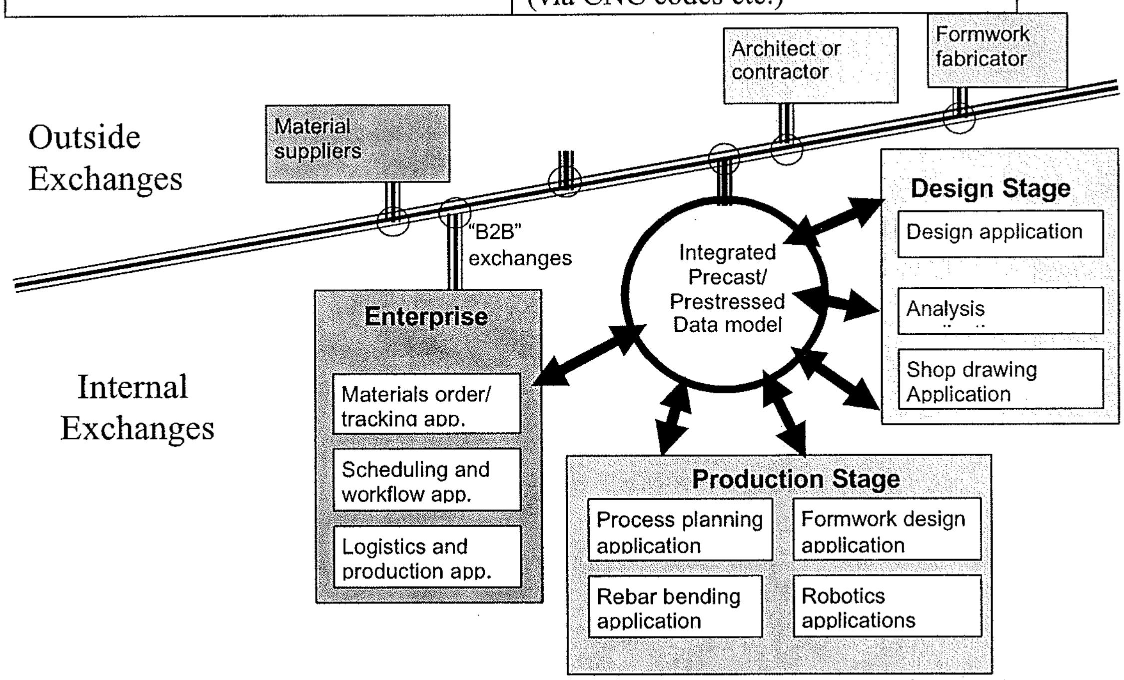

Fig. 1 Centralized Model Supporting Integrated Process [Sacks 2002]

1.2 Current vs. Envisioned Practice

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 this report.

Drawings are merely reports extracted from the 3D model. Current 3D modeling software applications provide a myriad of ways to customize the 2D drawings (e.g., plans and details) that are extracted from the 3D models, e.g., from text (label) fonts to piece marking conventions. If bridge owners persist in avoiding the adoption of recommended industry standards (e.g., [AASHTO/NSBA 2003]) for 2D presentation purposes, each of these uniquely owner-specific ways of presenting 2D drawings could be defined in templates that could then be invoked by the 3D modeling application to generate owner-specific 2D drawings automatically once the state-specific template is set up. Once such options are defined for a particular owner, they can remain transparent to the user need not be revisited until the owner changes its desired formats for 2D drawings and hardcopy output – for as long as they still continue to require hardcopy output. Thus, output reports extracted from the model and associated design information must be human-readable as well as machine-readable.

Table 2 Comparison of Current and Envisioned Future Practice

Status Quo	Future Vision
Proliferation of inconsistent, overlapping data standards	Coordinated widely used data standards
Time-consuming data transfer (often requiring re-entry) across applications	Open, nonproprietary data formats adopted industry-wide
Tedious, error-prone manual data re-entry	Automated transfer of data "entered once"
Limited access to information across functional stakeholder areas	Sharing of information across planning, design, construction, and operation
Technology change limits access to archived legacy data	Data archived in accessible, self-documenting format

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 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.

It is usually not possible to effect improvements to each of the three major concerns of bridge owners: quality ("better"), schedule ("faster"), and economy ("cheaper"). The potential benefits of integrated BrIM (Bridge Information Modeling) for bridges, however, actually extend to all three, as suggested in Table 3.

Table 3 Example Economic Benefits of 3D BrIM Approach

Description	Better	Faster	More Economical
Avoid tedious error-prone manual data re-entry	v	v	
Avoid errors due to inconsistent information on different sheets	v		v
Leverage design data into construction & beyond	v	v	v
Can avoid physical pre-assembly		v	v
Accelerated const'n via prefabrication "just-in-time"		v	

To state it another way, the business need for 3D BrIM (Bridge Information Modeling) stems from the following deficiencies of current practices [Davies 2005]:

Inefficient Production of Data
- Extra resources
- Missing Data
- Unclear Audit Trail

Unclear/Imprecise Information
- Missing detail
- Uncoordinated drawings

High Level of Risk
- Site Problems\RFI's
- Clashes
- Delays
- Claims
- Waste

A key source of quantitative data of this sort has been documented recently. A related industry, the Capital Facilities industry, has conservatively documented a loss of over $15 billion annually as a direct result of inadequate interoperability [Gallaher et al. 2004].

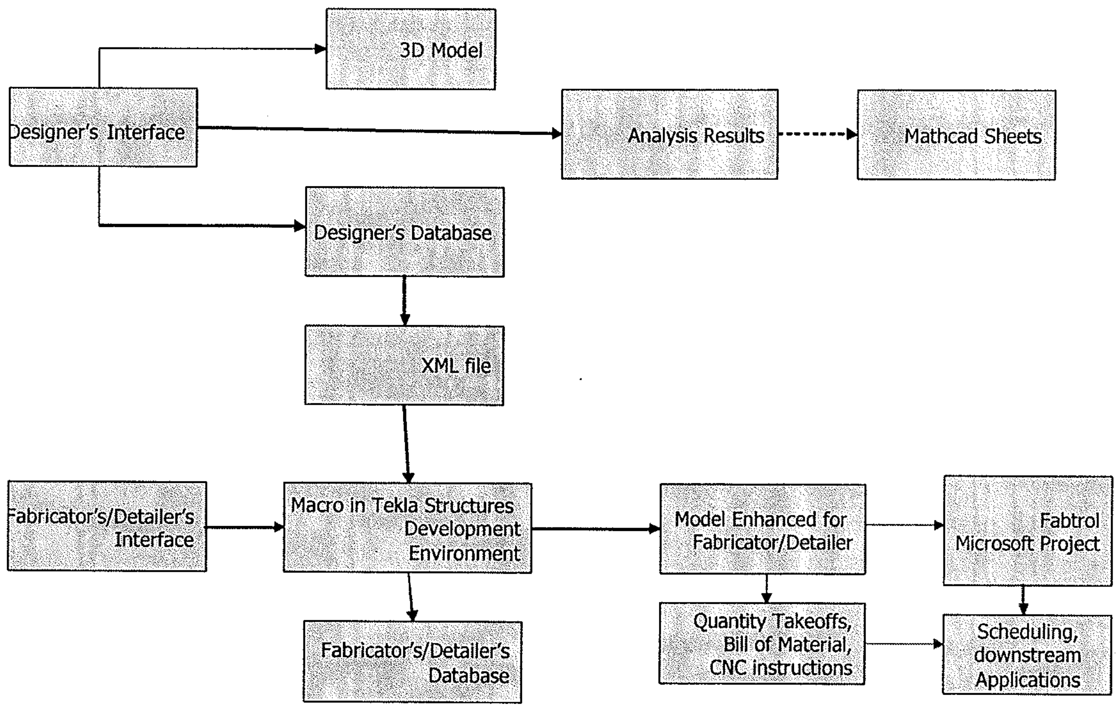

Fig. 2 Workflow Explored using 3D BrIM (Bridge Information Model) Approach

Other references describing background for this work, including indicators of how U.S. practice lags behind that in several European countries and Japan, include references [Tamai et al. 2002], [Verma et al. 2001], and [Chen 2002].

2. ENVISIONING AN INTEGRATED DESIGN AND CONSTRUCTION PROCESS

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. The principal software applications employed in this study were TriForma from Bentley Systems, Inc., and Tekla Structures from Tekla, Inc. Bentley is already dominant in DOTs and bridge design offices, and Tekla was selected by PCSC (The Precast Concrete Software Consortium) as the best platform for precast while already supplying a detailing solution for steel thus not being biased toward steel. Tekla's apparent weakness in the analysis realm is assumed to be addressed by the forthcoming linkage between SAP2000 (already excellent for seismic, moreover with a bridge module released in ver. 9) and Tekla Structures. Tekla is keenly interested in the bridge market. For demonstrating proof-of-concept one vendor may have been enough. But two were investigated in order to demonstrate that the approach need not be tied to one vendor and thus is indeed nonproprietary.

2.1 Bridge on Highway Alignment

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.

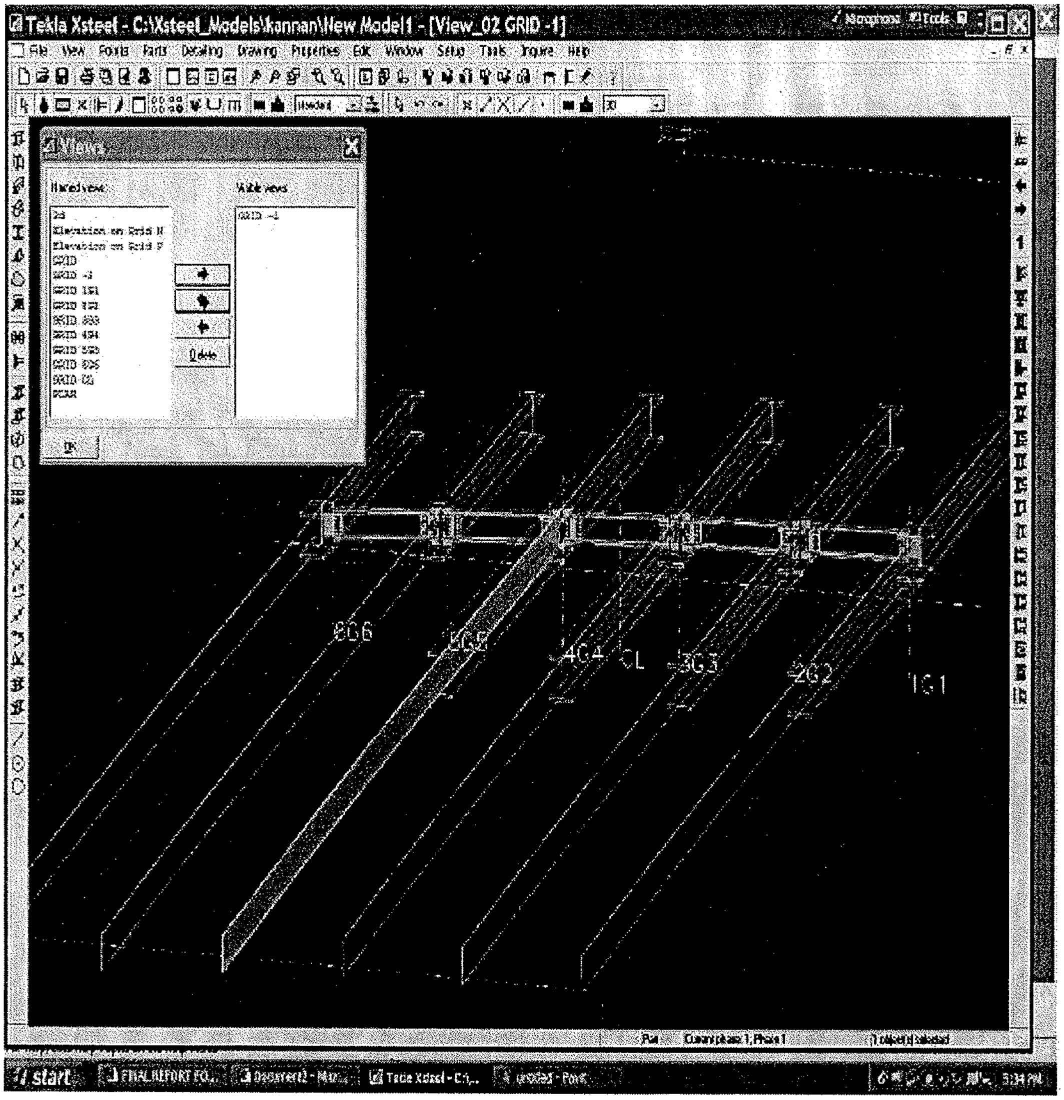

Fig. 3 Partial 3D Steel Bridge Model (Girder Portions and Diaphragms using Tekla Software) [Chen et al. 2003]]

Once the designer creates the model, he exports it in a suitably exchangeable form (e.g., XML, as implemented in this project). In industrial deployment, this XML could be some blend of emerging dialects like transXML [NCHRP 2005] 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 model (and/or drawings extracted from it), the fabricator would log into his section of the website and can review the model (and/or drawings extracted from it) in the fabricator's section of the project website – without needing a license for the software that the designer used to generate them. The fabricator would be able to inspect and electronically comment (i.e., issue RFI's) on 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 and maintaining the ideals of single-data entry as implemented in this project.

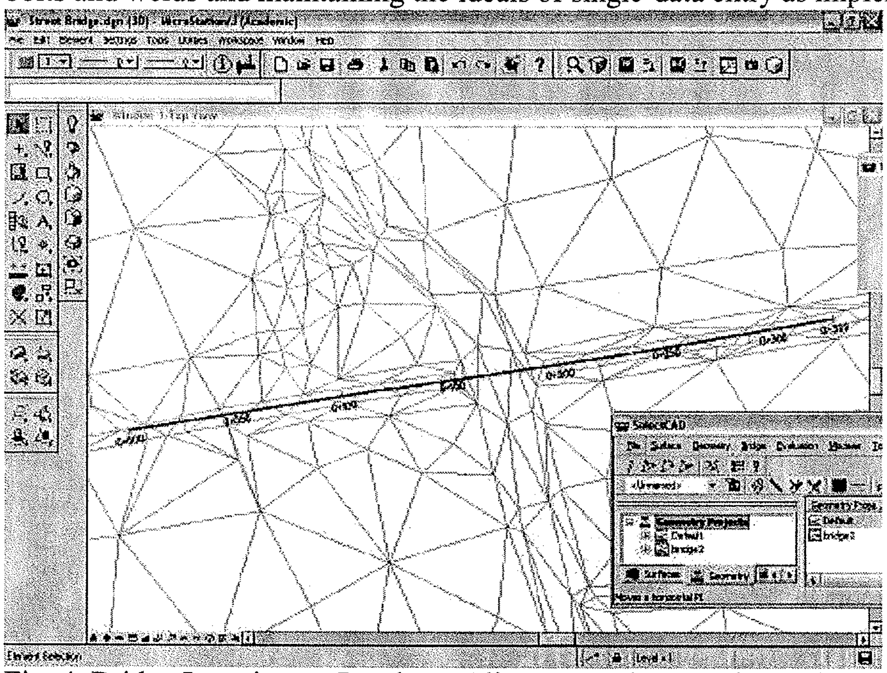

Fig. 4 Bridge Location on Roadway Alignment using Bentley Software (www.bentley.com) [Chen et al. 2003]

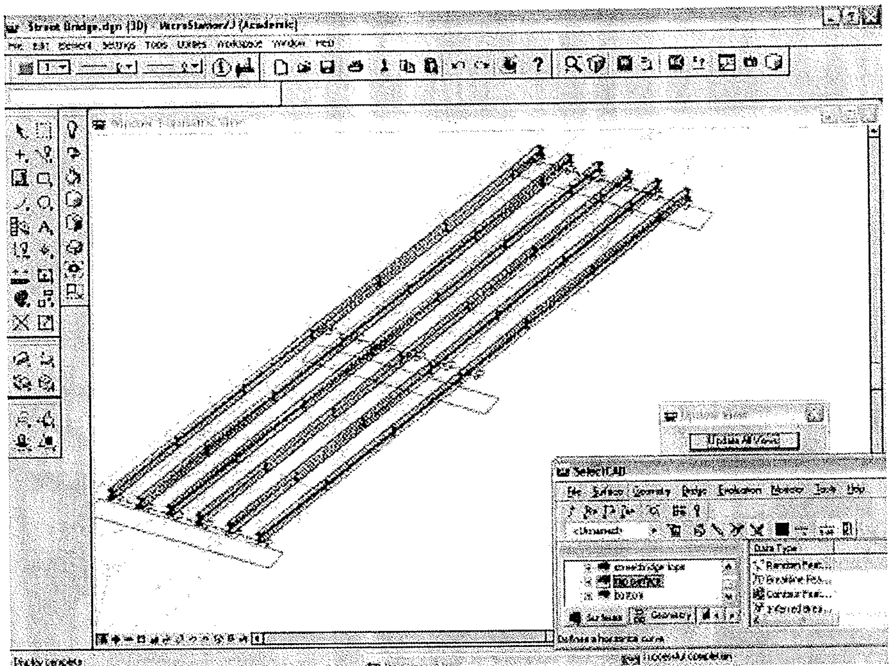

Fig. 5 3D Model of Steel Bridge Framing using Bentley Software (www.bentley.com)

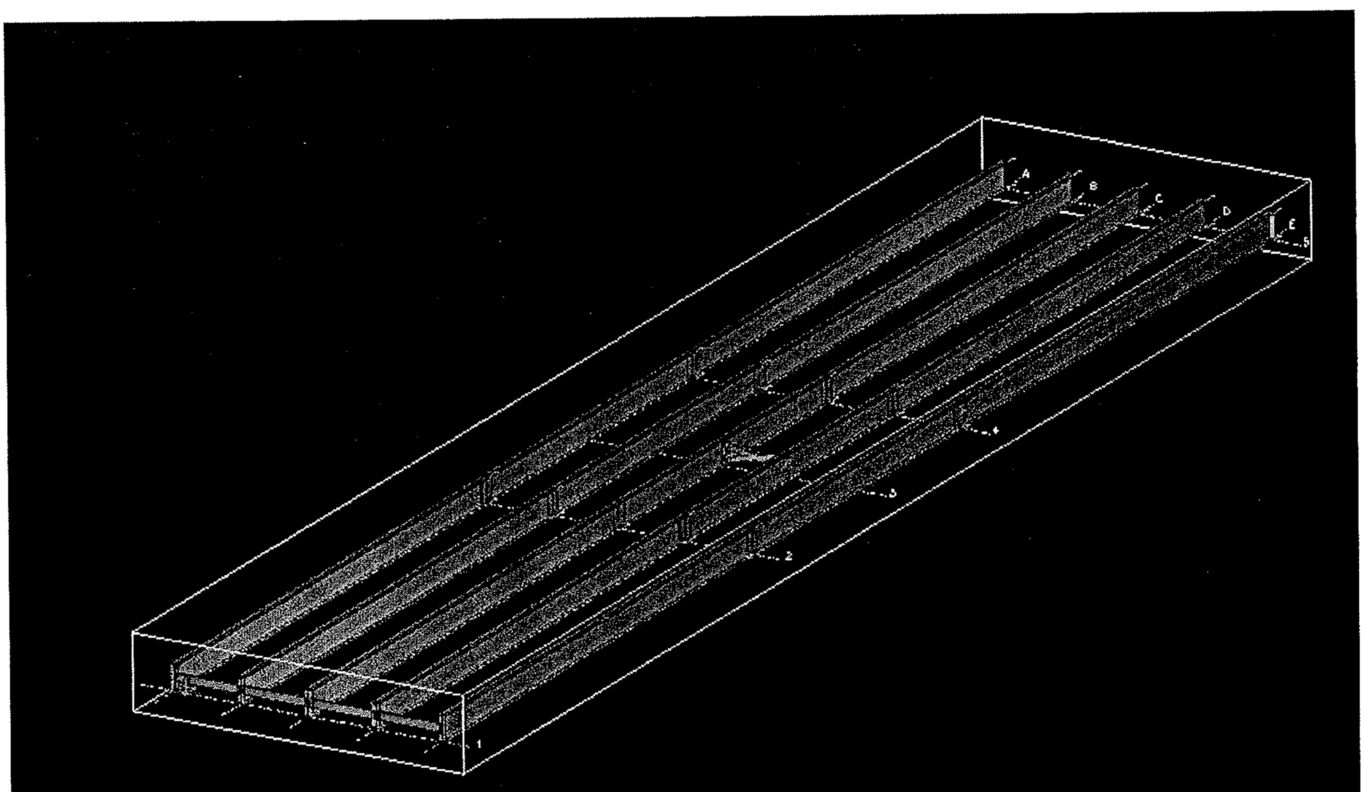

Fig. 6 3D Model Detailing Under Construction in Detailing Software (www.tekla.com)

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 (such as generation of 2D design drawings and shop drawings, and quantity takeoffs for cost estimating or material ordering) 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.

2.2 Downstream from Design and Detailing

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. For the bridge application further downstream leveraging of the bridge geometry data would occur with
- Erection engineering and procedure generation, including interference checking.

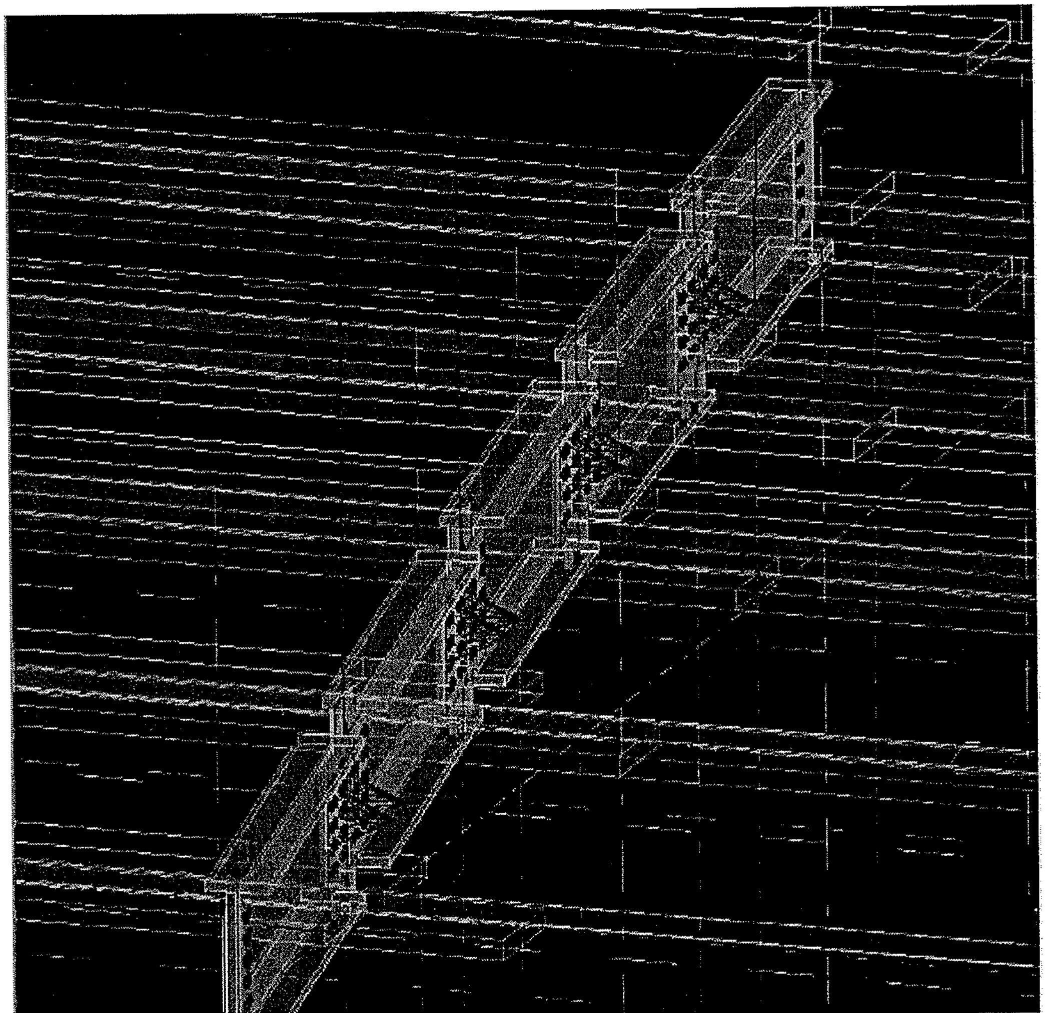

Fig. 7 Diaphragm Placement in 3D Model using Tekla Software (www.tekla.com)

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, as implemented in this project. 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.

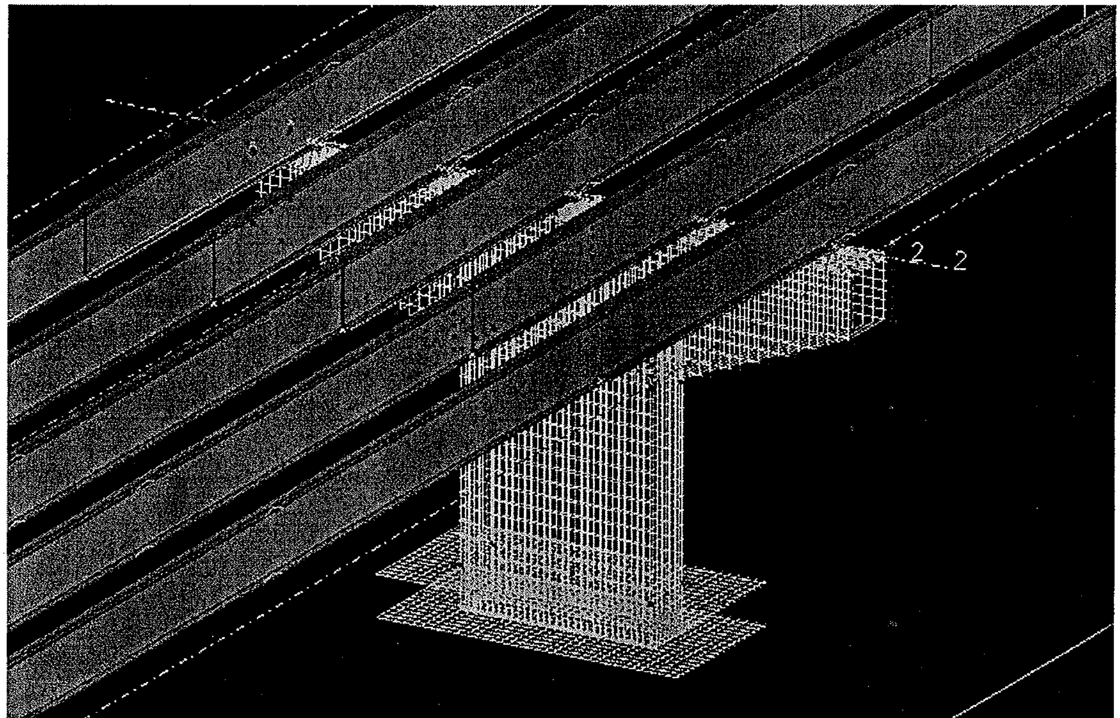

Fig. 8 Pier Detailing in 3D Model using Tekla Structures (www.tekla.com)

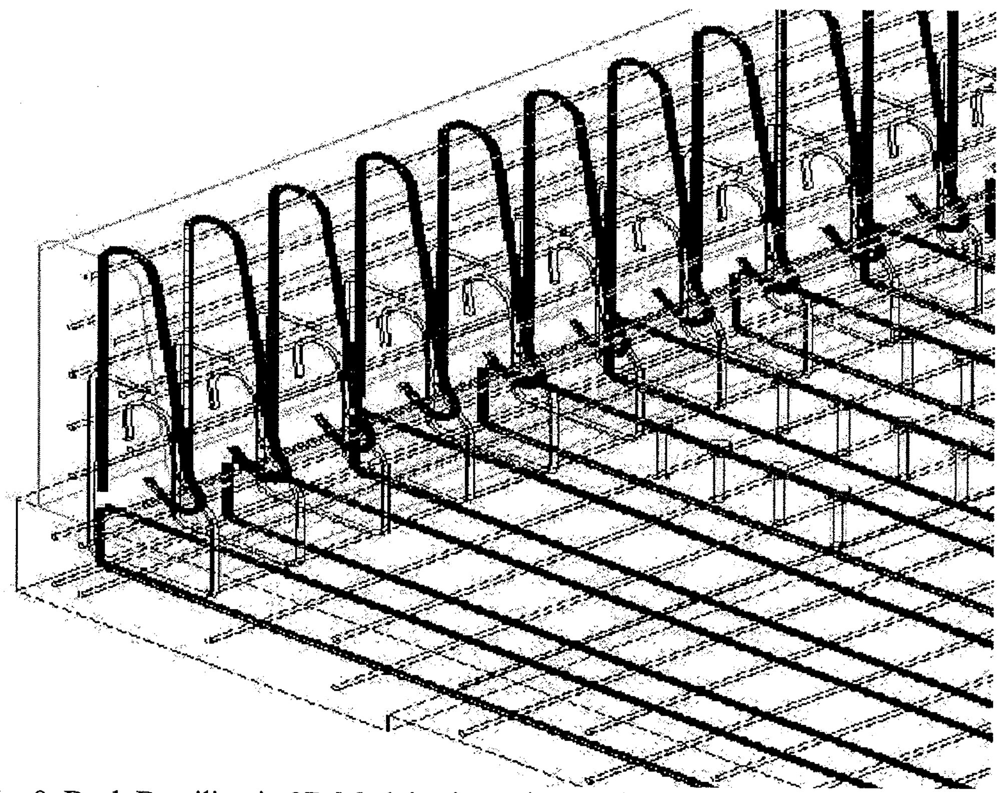

Fig. 9 Deck Detailing in 3D Model using MicroStation TriForma (www.bentley.com)

Table 4 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	191985.2	191985.2	kg	$3.00	$575,955.60
Superstructure	HPS Steel S	High performance weathering steel for plate girders S. bound	kg	191985.2	191985.2	kg	$3.00	$575,955.60
						Grand Total		$1,526,280.00

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.

2.3 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,
- A reduced number of technical queries [Davies 2005], which translates into reduced fabrication/construction costs,

- 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 [McDowell 2005],
- Tighter coordination and the discovery of fitup problems before stumbling on them in the field, where those discoveries were made in time to initiate changes relatively painlessly [Mueller 2004],
- 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 ([FIATECH 2004], [Khanzode and Fischer 2000], [Post 2003], [Sacks 2004], [Sacks et al. 2005)).

3. 3D-CENTRIC BRIDGE INFORMATION MODELING IMPLEMENTATION

In order to ensure that the evolving development effort was genuinely focused on the practical concerns of the bridge community, meetings and discussions were held with various stakeholders, including owners, designers, contractors, subcontractors, suppliers, software developers, standards organizations, etc. These meetings and presentations included the following:

- "3D Parameterization Precedes Pervasive Prefabrication," presented to the 2nd National Prefabricated Bridge Elements & Systems Workshop, USDOT/FHWA, New Brunswick, NJ, Sept. 2004,
- "3D-Centric Process for Integrated Bridge Design and Construction," to the Annual Meeting of the North Central States Consortium, Minneapolis, MN, Sept. 2004,
- Presentation and Demonstration to PennDoT Chief Engineer M. G. Patel, Harrisburg, PA, Oct. 2004,
- Presentation and Demonstration to TRB Committee AFH70 (Fabrication and Inspection of Metal Structures), Washington, D.C., January 2005,
- Presentation and Demonstration to High Steel Structures, Inc., March 2005,
- Presentation and Demonstration to PennDoT District Execute and Staff in the District containing one of the case study bridges modeled in this work, Allentown, PA, April 2005,
- Presentation and Demonstrations to Lead 3D Building and Bridge Software Developers of Bentley Systems, Inc., at BE (Bentley Empowered) International User Conference, Baltimore, MD, May, 2005,
- Participation in a series of conference calls and software demonstrations involving FHWA personnel, owners, contractors, fabricators, software developers, and researchers on the subject of integrated design and construction of bridges, April – July 2005,
- Presentation to Bridge Design Workshop of the ABCD (Association for Bridge Construction and Design), Albany, NY, June 2005,
- "Computer-Integrated Bridge Fabrication," presentation to AASHTO SCOBS (Subcommittee on Bridges and Structures), Newport, R.I., June 2005,

- "Accelerating the Bridge Project Delivery Process: A Roadmap," [Shirole' and Chen 2005] presentation to the 3rd National Prefabricated Bridge Elements and Systems Workshop, San Diego, CA, Nov. 2005, and
- "Integration of Information and Automation Technologies in Bridge Engineering and Management: Extending State of the Art," [Chen and Shirole' 2006] presentation at the Annual Meeting of the Transportation Research Board, Washington, D.C., January 2006.

3.1 Parametric Modeling and Downstream Leveraging

This section illustrates various aspects of the workflow introduced earlier in Fig. 2.

3.1.1 Steel Girder Superstructures

One of the bridges parametrically modeled in this work was based in part on a detailed worked design example [Repp and Chen 2005]. Documented in MathCad, which is inherently parametrically driven, the parameterization effort performed there for the purpose of ensuring compliance with AASHTO design checks was leveraged into the 3D model generation. Line-girder analysis was implemented (for shear and moment envelope generation) using the WSDOT (Washington State DOT) Bridge Foundation Libraries. V-load analysis was implemented separately for curved girder bridges. A designer's interface as shown in Fig. 10 was coded in VBA (Visual Basic for Applications) to run in the MicroStation/TriForma Bentley software environment for 3D model generation from the parameters after they were stored in a Microsoft Access database from which they could drive not only the line girder analyses and AASHTO design checks but also subsequent model generation and data extraction from that model.

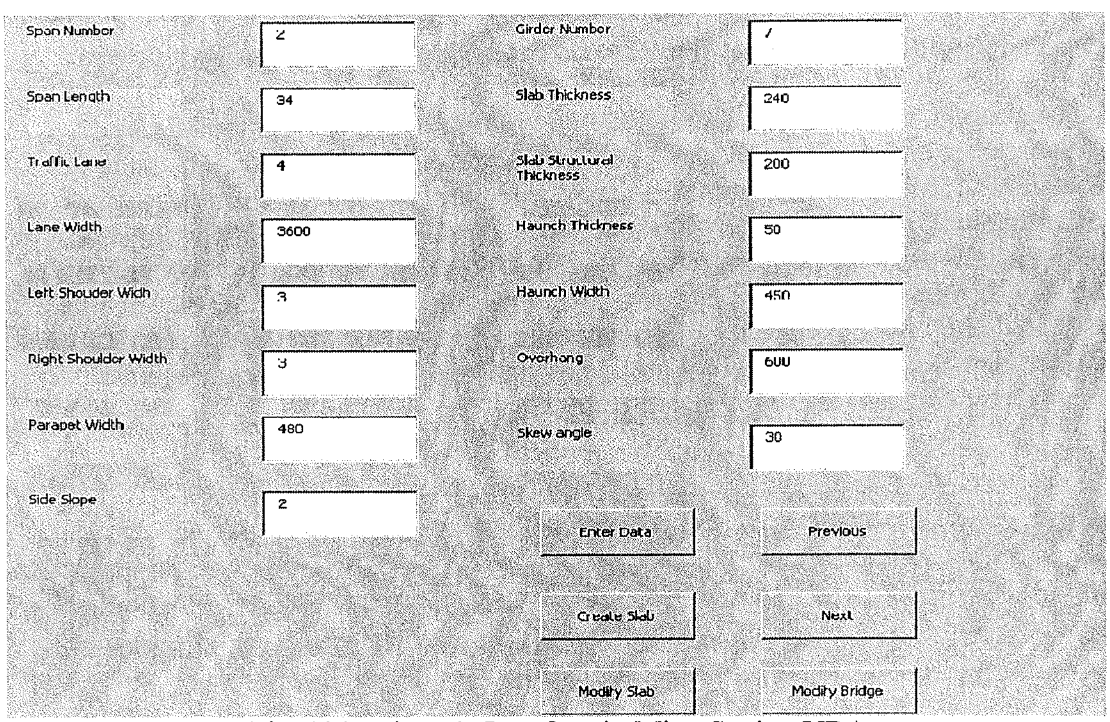

Fig. 10 Designer's Interface in MicroStation VBA

Fig. 11 shows the 3D model generated directly from the driving parameters. With this capability, no CAD operator is needed to generate the 3D model from which drawings can be extracted. Thus, fundamentally it is the underlying data that is key, not the fact that it can be viewed using CAD/CAM software or even used to drive fabrication using CAD/CAM software. Figure 10 highlights that the data itself is the fundamental driver and that in fact the envisioned extraction of data does not depend upon the 3D CAD/CAM model generated from that data. As such, 3D CAD/CAM software (such as that rendering Fig. 11) should be thought of as just one way of extracting/viewing the data.

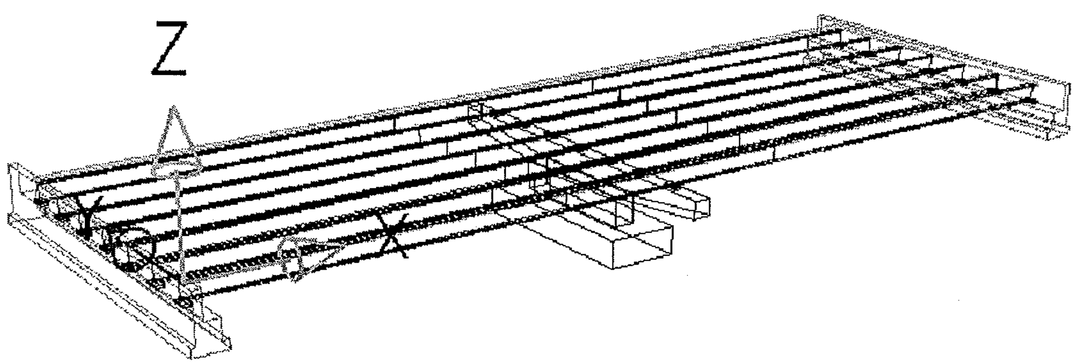

Fig. 11 Two-Span Continuous Steel Plate Girder Bridge Model in Bentley Software

The same parameters, maintained (once entered from a single entry point) in the Microsoft Access database, are exported as an XML (Extensible Markup Language) file. This form of export is doubly appealing in that it provides the option to post the data on a project website, as described earlier in this report. The XML file in turn is parsed by a C++ macro programmed in the Tekla Structures software environment in order to generate the 3D model shown in Fig. 12. The reason for doing all this apparently "extra" programming is to maintain the ideal of single data entry and illustrate parameter-driven geometry generation directly in the detailing software environment. Here it can be edited by the detailer as appropriate and can directly support downstream fabrication and construction operations.

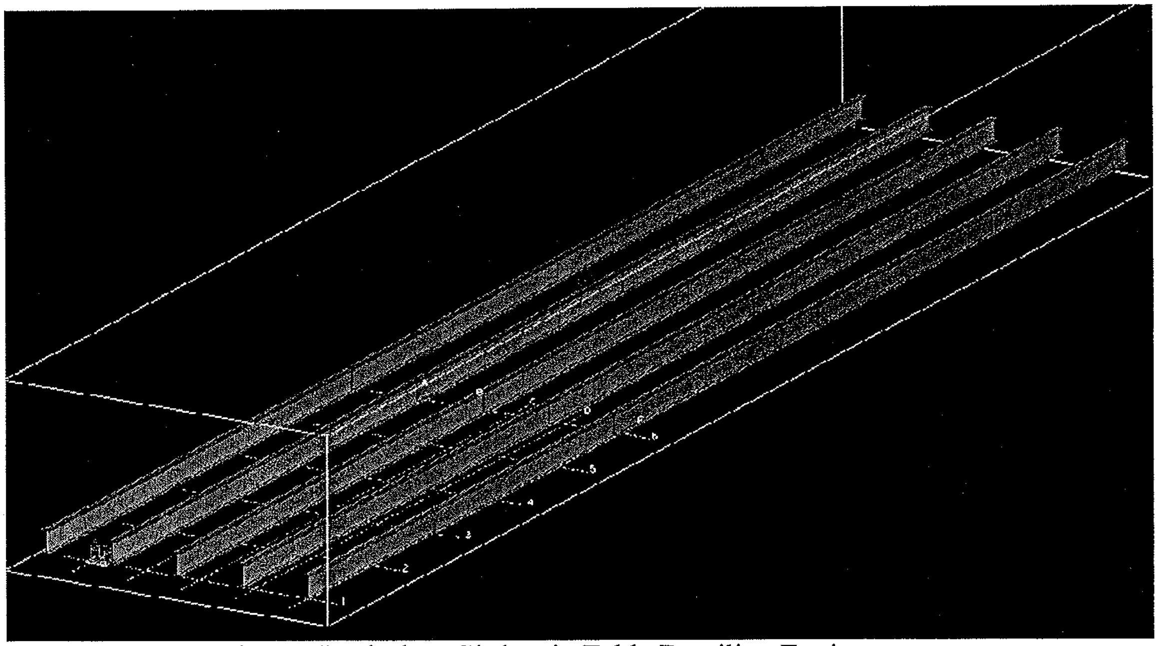

Fig. 12 Steel Plate Girders in Tekla Detailing Environment

Figure 13 shows an example XML file containing steel girder superstructure data. Normally it would be transparent to the user.

<?xml version="1.0" encoding="UTF-8" ?>
<dataroot xmlns:od="**urn:schemas-microsoft-com:officedata**" xmlns:xsi="**http://www.w3.org/2001/XMLSchema-instance**" xsi:noNamespaceSchemaLocation="**demotest3.xsd**" generated="**2005-03-09T19:47:48**">
<demo>
<bridgeid>**1**</bridgeid>
<Numberofspans>**2**</Numberofspans>
<spanlength>**40000**</spanlength>
<Numberofgirders>**5**</Numberofgirders>
<Lanewidth>**3600**</Lanewidth>
<leftshoulderwidth>**1200**</leftshoulderwidth>
<Rightshoulderwidth>**3000**</Rightshoulderwidth>
<Overhangwidth>**600**</Overhangwidth>
<pWidthtopflange>**450**</pWidthtopflange>
<pThicknesstopflange>**38**</pThicknesstopflange>
<pdepthweb>**1300**</pdepthweb>
<pthicknessweb>**14**</pthicknessweb>
<pwidthbottomflange>**450**</pwidthbottomflange>
<pthicknessbottomflange>**25**</pthicknessbottomflange>
<factorofspan>**1**</factorofspan>
<nWidthtopflange>**450**</nWidthtopflange>
<nThicknesstopflange>**40**</nThicknesstopflange>
<ndepthweb>**1300**</ndepthweb>
<nthicknessweb>**14**</nthicknessweb>
<nwidthbottomflange>**540**</nwidthbottomflange>
<nthicknessbottomflange>**40**</nthicknessbottomflange>

<numberoflanes>**3**</numberoflanes>
</demo>
</dataroot>

Fig. 13 Steel Girder Superstructure XML

An XML schema is a set of rules describing the types of information that can, or must, appear in an XML document. For proper generality, such an XML schema should be developed as an industry standard. Such a standard in support of downstream fabrication and construction concerns does not exist. For the purposes of this project, a schema needed to process the above file was defined and coded as a C++ implemented in the Tekla Structures development environment. Part of this parser is illustrated in Fig. 14. The XML file parameters are stored in an array and used in built-in functions provided by the Tekla API (Application Programming Interface) to create plates and members. The detailer then works on the generated model to create secondary members, welded and bolted connection details, etc. A partially detailed model is shown in Fig. 15. Such a model in turn can export an updated XML file for data transfer downstream.

```
#include "e3user.h"                    / Including header files provided by Tekla
#include "joint_dbase.h"
#include "usercomm.h"

#using <mscorlib.dll>                  /Using Dynamic link libraries built in Dotnet
#using <System.Xml.Dll>

using namespace System;                /Using Namespaces provide in Dotnet
using namespace System::Xml;
using namespace System::IO;

int user_macro_9(macro_t *macro)       /User macro defined by us, Takes a single point input
{
  char name[20];
      double height,width,thickness;     /Defining variables to be used later in the program
  int nplates,idc1,idc2,idc3,weldno1,weldno2,ii,diaphr,stiffner,j,i1;
      char pos[20],ass_pos[20],partname[20],material[20];

      int input[100];
      point_ p1;
          xs_line_t line1;
      welding_parameter_t weld;
                                       /Opening the XML file
      String *document="demo1.xml";

  XmlTextReader* reader =0;

  reader = new XmlTextReader(document);

  i1=0;

  while(reader->Read())                /reading the XML file
{
       switch(reader->NodeType)
       {
               case XmlNodeType::Element:

                       break;
       case XmlNodeType::Text:

               input[i1] = System::Int32::Parse(reader->Value); /Reading the XML file into an array and parsing into an Integer

               Console::WriteLine(input[i1]);           /Writing the input onto the console as a cross check
       i1=i1+1;
```

```
                break;

                case XmlNodeType::EndElement:
                        break;      }
}

for(ii=0; ii<input[3];ii++)                    /Creating plate Girders , If u observer the fourth parameter is the number of girders
    {
 xs_point(&line1.p1, p1.x-(ii*1206.72), p1.y, p1.z);
    xs_point_add(&line1.p2,line1.p1, 0, 0,input[13]);
    strcpy(ass_pos,"A_MACRO\\1");
    strcpy(pos,"XS\\2");
    strcpy(partname,"XSPLATE");
    strcpy(material,"FE360B");
    xs_part_attributes(ass_pos,pos,partname,material,1,2);
    xs_position_attributes(0.0,0.0,MIDDLE, 0.0, TOP, 90.0, MIDDLE, 0.0);

 idc1 = xs_plate (input[2],input[12],line1);                         /Creating the botom flange
    printf("%d\n",idc1);
 printf("Plate1 is created\n");

 xs_point(&line1.p1,p1.x-(ii*1206.72),p1.y,p1.z+input[13]);
    xs_point_add(&line1.p2,line1.p1,0,0,input[10]);

 idc2 = xs_plate(input[2],input[11],line1);                          /Creating the web
    printf("%d\n",idc2);
    printf("plate2 is created\n");

    xs_point(&line1.p1,p1.x-(ii*1206.72),p1.y,p1.z+input[13]+input[10]);
    xs_point_add(&line1.p2,line1.p1,0.0,0.0,input[9]);

 idc3 = xs_plate(input[2],input[8],line1);                           /Creating the Top flange
 printf("%d\n",idc3);
    printf("Plate3 is created\n");
```

Fig. 14 Portion of XML Parser Code

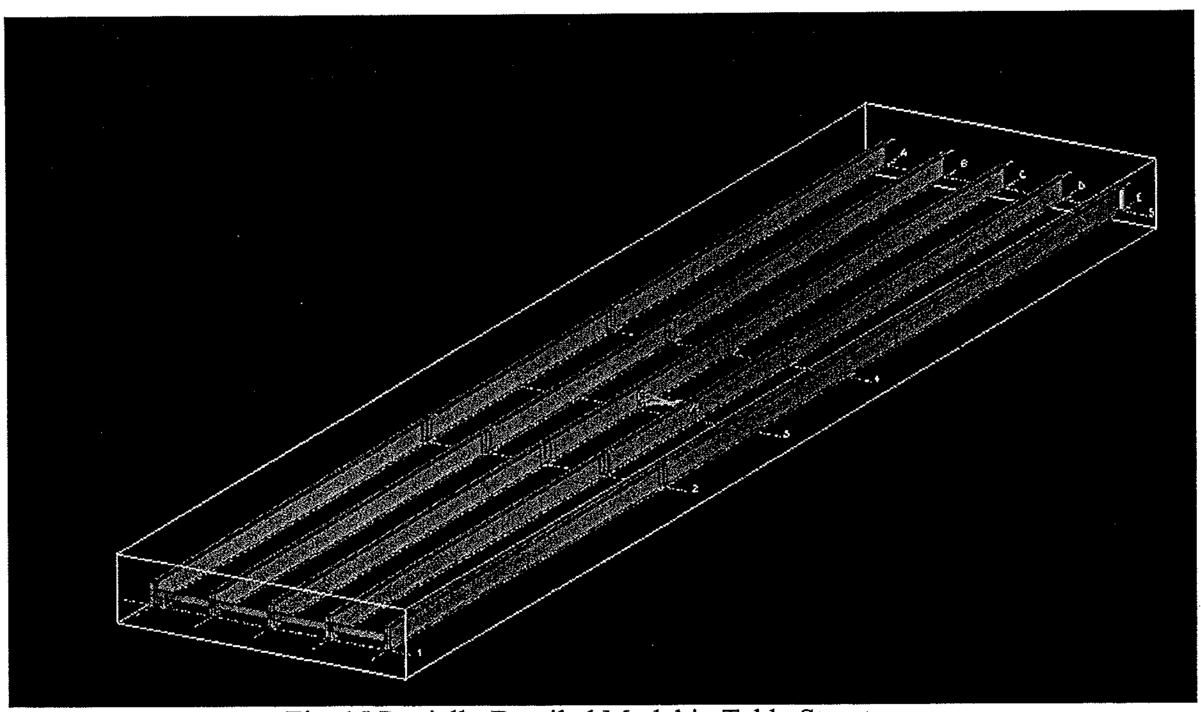

Fig. 15 Partially Detailed Model in Tekla Structures

3.1.2 Distinct Geometries

Interoperability aspects aside, complicating 3D geometry modeling is the fact that more than one distinct geometry is of interest. Fabricators and erectors must be concerned with three. These are ideally distinct on the camber diagrams of a typical contract plan set and have been described as follows [Beckmann and Mertz 2005]:

- Stage I-No load condition,
- Stage II- Steel dead load condition, with cross frames in place, and
- Stage III- Full dead load condition.

Fig. 16 illustrates these stages.

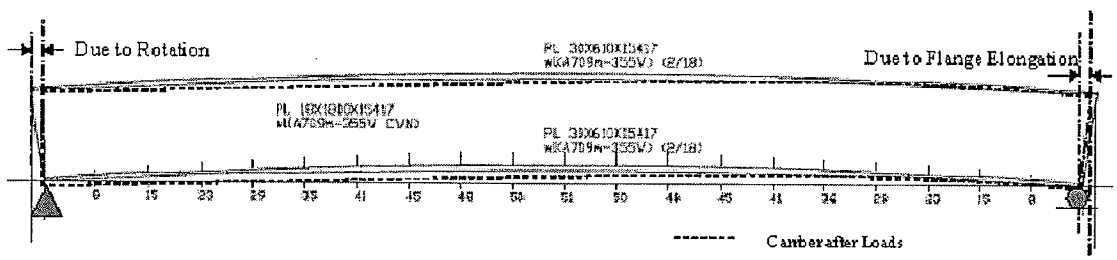

Fig. 16a Distinct Geometries Needing Modeling: Stage III (Full Dead Load)

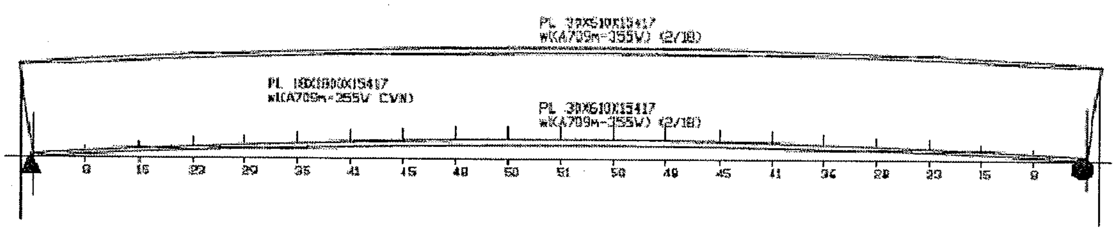

Fig. 16b Distinct Geometries Needing Modeling: Stage II (Steel Dead Load)

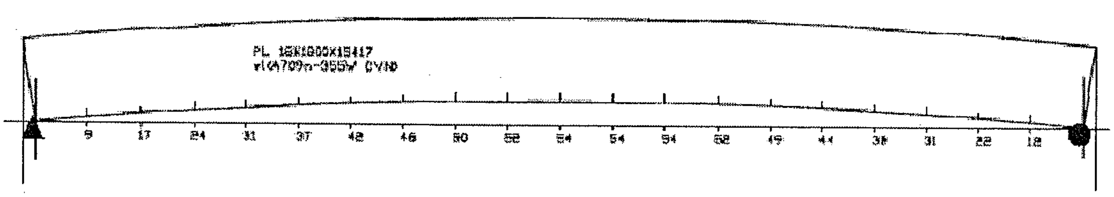

Fig. 16c Distinct Geometries Needing Modeling: Stage I (No Load Condition)

In general, for skewed and horizontally curved bridges, in only one of these stages can the girder webs be vertical in the fabricated and erected position. A preliminary effort was undertaken to implement the programming of distinct geometries directly within the Tekla 3D modeling/detailing software. This programming was implemented using the C++ based macro programming capability provided in the developers' version of the software and calculates deflections and rotations within the 3D modeling environment [Sultana 2005].

Each geometry is of interest since we are intending the model to be used not only to bid from but also to build from. As such, for example:

- Stage III (no load) geometry is of interest for, e.g., cutting girder web plates,
- Stage II (steel dead load) geometry is of interest for, e.g., hole placement to ensure proper fit-up via "virtual assembly" – which would save considerable time and cost compared to the current practice of physical pre-assembly (a.k.a. "laydowns" in the fabricator's yard prior to disassembly and shipment), and
- Stage I (full dead load) geometry is of interest to comply with highway geometric alignment.

3.1.3 Curved Superstructures

Modeling capabilities are not limited to straight bridges. Figure 17 shows a view of a 2-span continuous horizontally curved bridge on a skewed pier being modeled in the Tekla Structures software. This software is normally used in the building and plant industries rather than the bridge industry. It was found to be usable for bridge modeling as well, but without some of the amenities that a highway bridge engineer would want to have (e.g., generation of bridge geometry directly from highway alignment geometry).

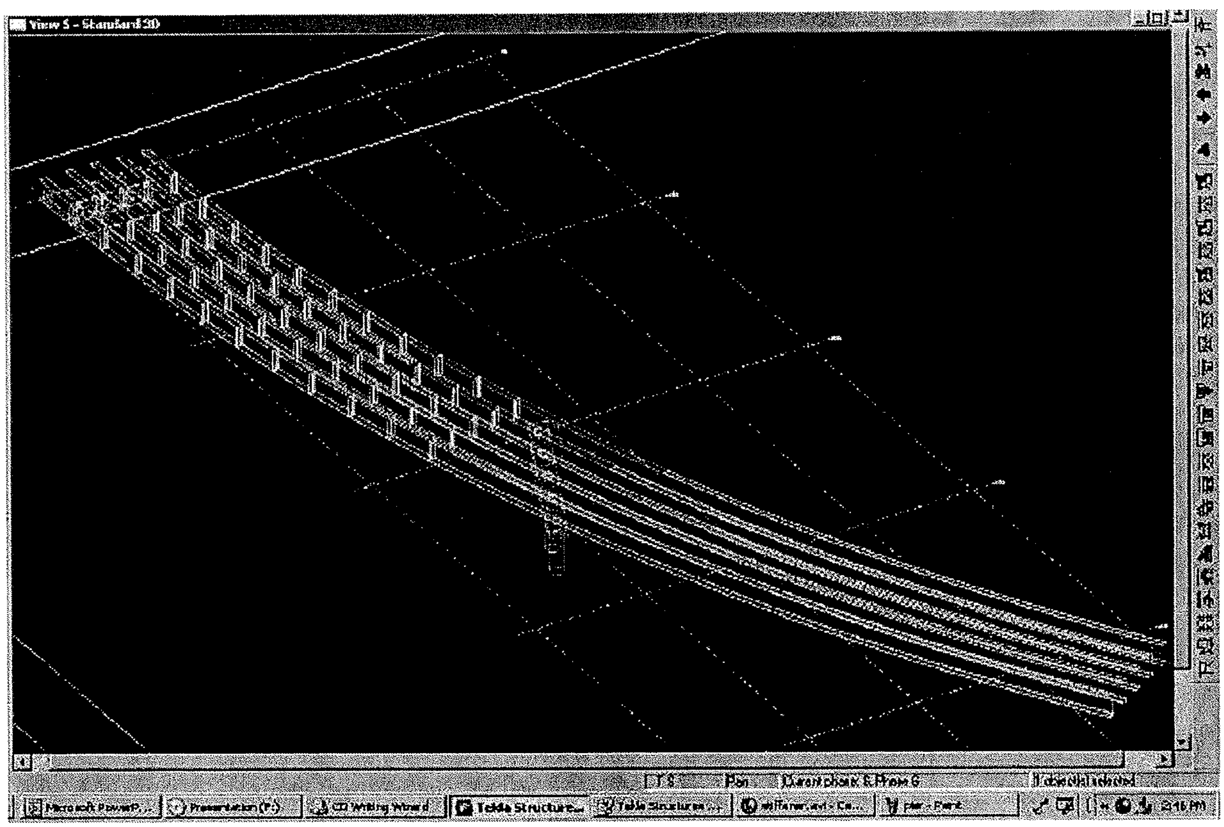

Fig. 17 Horizontally Curved Bridge Being Modeled using Tekla Software

Fig. 18 shows another horizontally curved bridge modeled in 3D, this one using Bentley software.

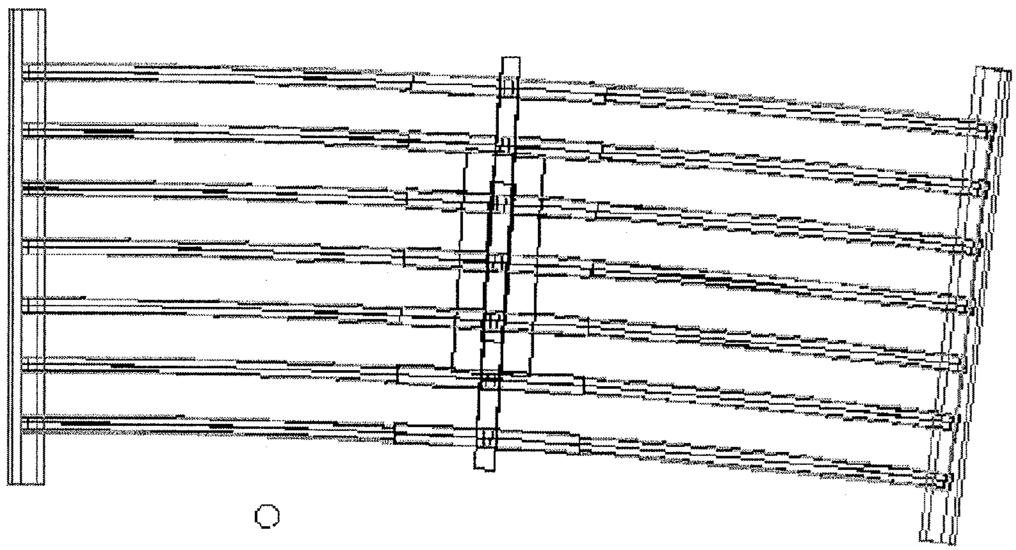

Fig. 18 Horizontally Curved Bridge Modeled using Bentley Software

3.1.4 Concrete Bridges and Substructures

Modeling capabilities are not limited to steel girder superstructures. PennDoT provided plans for a bridge replacement project in Northampton County. It is a single span composite prestressed concrete I-beam bridge carrying a curved alignment – thus superelevated - and on a slope as well. It provided the principal test case for reinforced and prestressed concrete bridge modeling in 3D as well as for abutment modeling. Fig. 19 shows the parametrically generated girders transferred into the Tekla Structures detailing software environment in the same manner as the steel bridge girders were transferred for the same reasons – to maintain single-data-entry ideals.

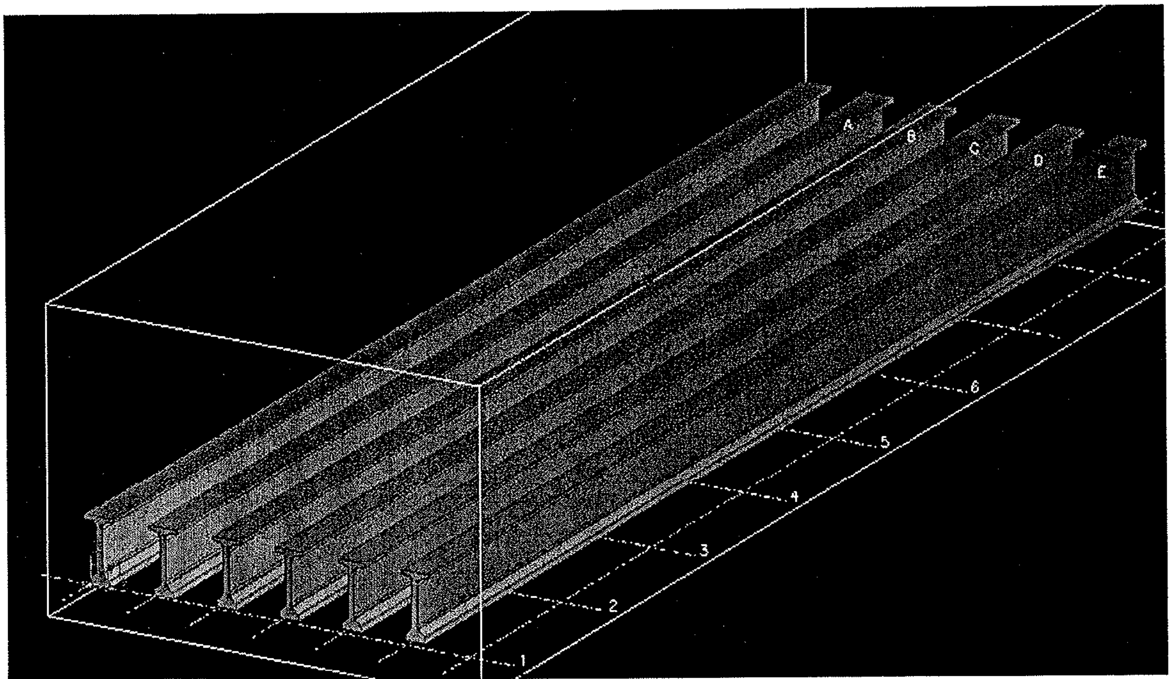

Fig. 19 Precast Prestressed Girders in the Tekla Detailing Environment

Fig. 20 shows these girders after adding detailing information.

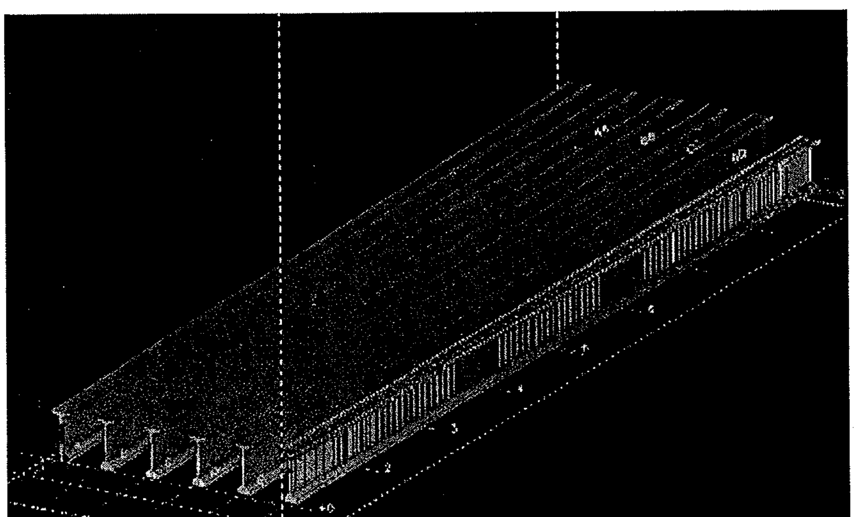
Fig. 20 Precast Prestressed Girders with Detailing Information in Tekla Environment

Views of strand and stirrup reinforcing are shown in Fig. 21.

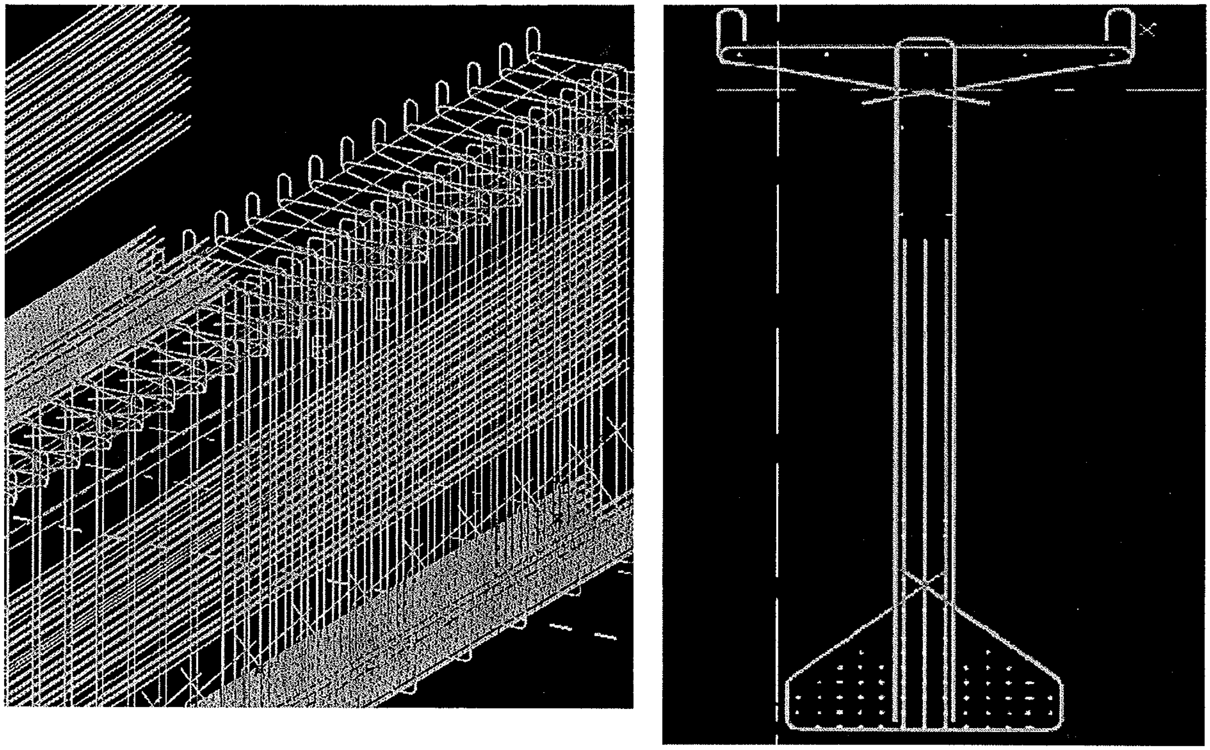

Fig. 21 Views of Strand and Stirrup Reinforcing Extracted from Model

Substructure models were developed for the pier of the steel plate girder bridge and for the abutment of the prestressed concrete girder bridge, with data transferred into the detailing environment as it was done for the girders as described above. Fig. 22 shows the pier of the steel bridge, and Fig. 23 shows the reinforcing steel detailed for it.

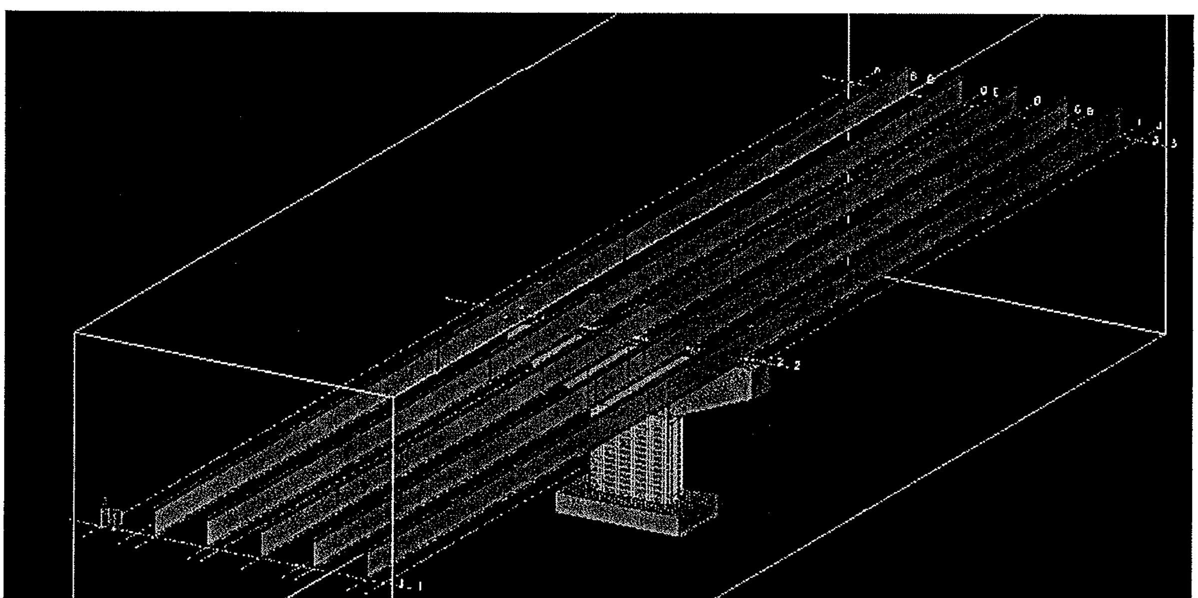

Fig. 22 Model of Bridge Pier

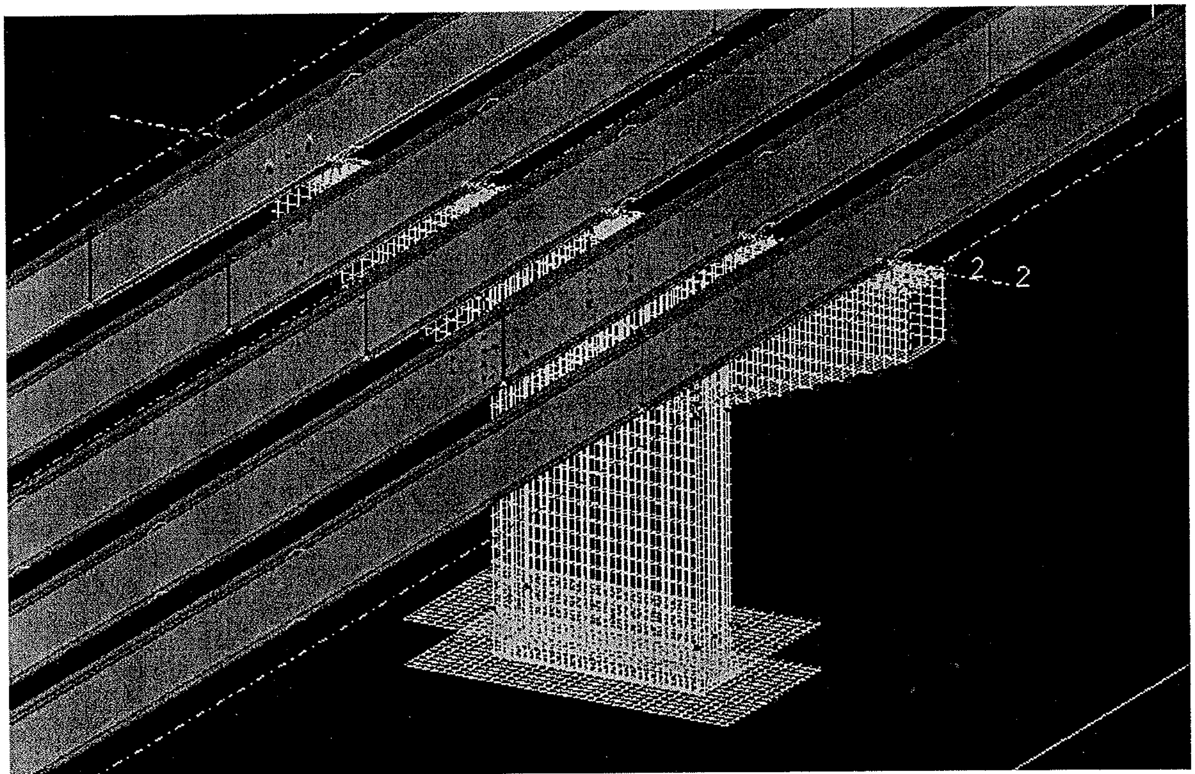

Fig. 23 Rebar Detailing for Bridge Pier

Fig. 24 shows the abutment parametrically transferred into the 3D Tekla detailing environment.

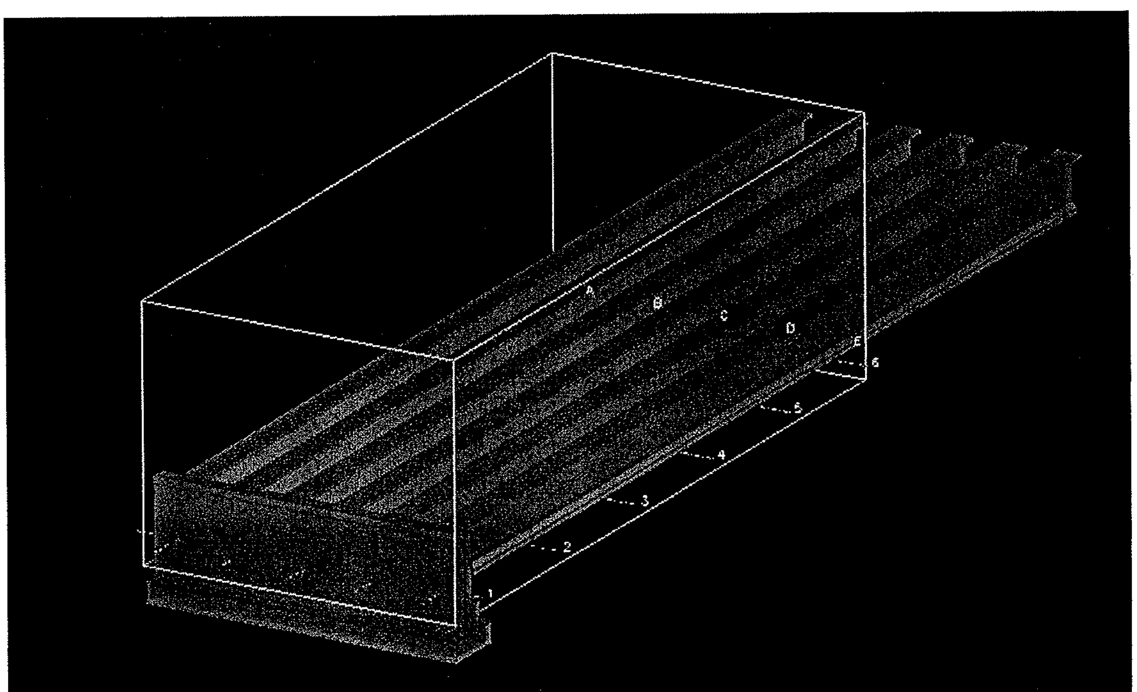

Fig. 24 Abutment Transferred into 3D Tekla Detailing Environment

Fig. 25 shows the abutment with detailing added to the model.

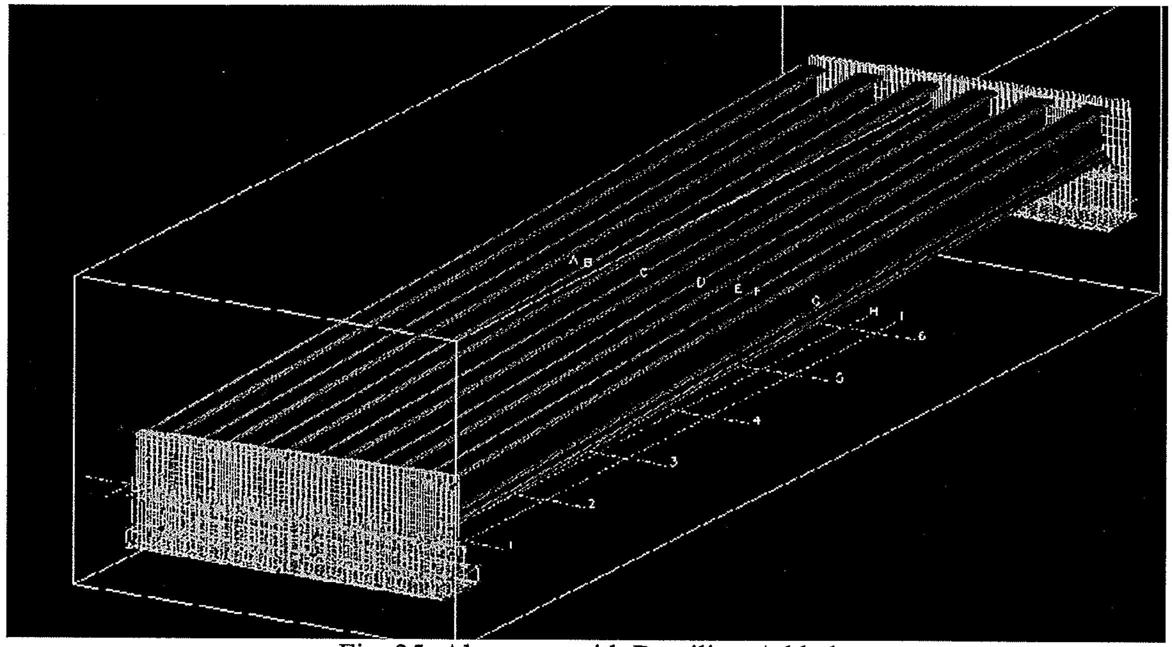

Fig. 25 Abutment with Detailing Added

Fig. 26 shows another view of the detailed abutment.

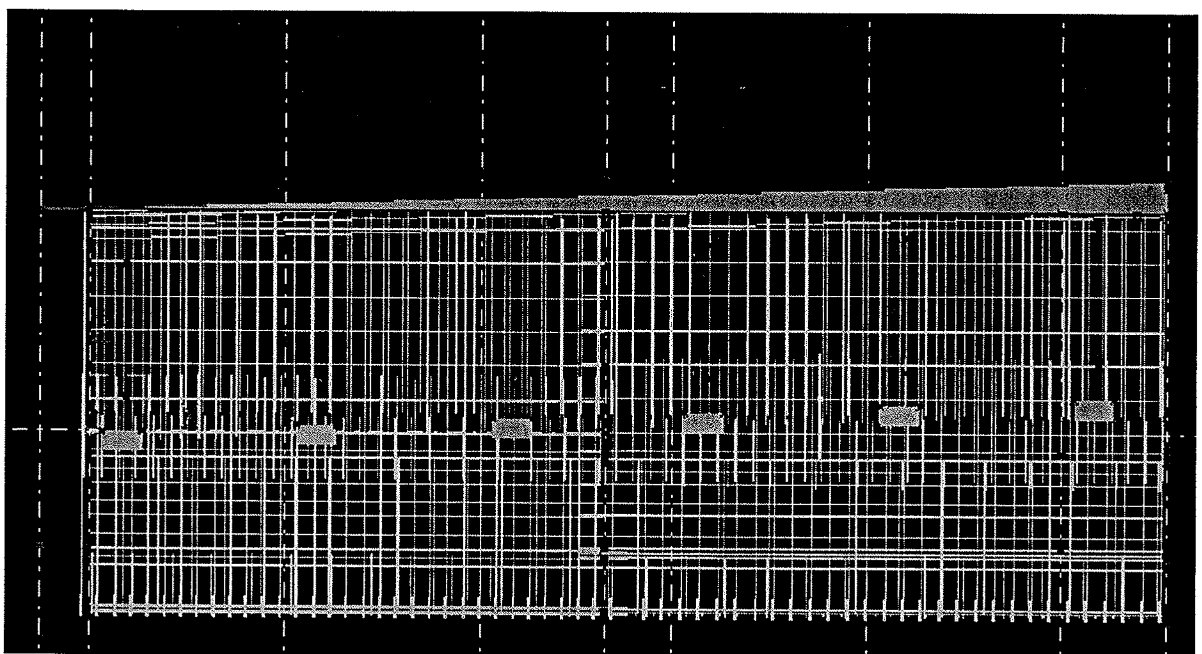

Fig. 26 Another View of Detailed Abutment

A key benefit of the 3D modeling effort is the leveraging of design and detailing information for downstream operations such as material estimating and/or ordering and CNC-driven fabrication. Figure 27 shows a partial reinforcing steel (rebar) material list generated directly from the model. In a similar manner, steel cut lists can be generated. CNC instruction files can also be exported directly, such that fabrication could theoretically begin immediately at a fabricator equipped with CNC plate-burners and CNC rebar bending machines if suitable material inventory were already on-hand.

```
REBAR BENDING SCHEDULE                    CONTRACT NO: FIRM
Page:1
                              CONTRACT:   TEKLA , Inc                     Date:06/19/2005
------------------------------------------------------------------------------------------
 No. Grade  Size Length Mark Type A   B   C   D   E   F   G   H   H2   J   K   K2   O   R
lbf/one lbf/all
------------------------------------------------------------------------------------------
128 A615-40  #4 2'-7"    15  A 2'-7"                                   1.7    220.9
112 A615-40  #4 3'-10"   17  Y                                         2.6    286.8
116 A615-40  #4 12'-9"    7  D 9'-6 0'-11 2'-6                         8.5    987.9
 60 A615-40  #5 4'-7"     5  B 3'-6  1'-2                              4.8    287
 92 A615-40  #5 6'-5"     6  A 6'-5"                                   6.7    616
 72 A615-40  #5 8'-8"     9  A 8'-8"                                   9      651.2
 43 A615-40  #5 21'-0"    3  A 21'-0                                   21.9   942.3
 14 A615-40  #5 23'-0"    4  A 23'-0                                   24     336
 29 A615-40  #5 24'-1"   23  A 24'-1                                   25.1   728.8
  6 A615-40  #5 44'-4"    8  A 44'-4                                   46.3   277.6
116 A615-40  #6 9'-8"     2  B 8'-2" 1'-7                              14.5   1684.8
  4 A615-40  #6 21'-2"   11  A 21'-2                                   31.8   127.2
 10 A615-40  #6 22'-2"   21  A 22'-2                                   33.3   333.1
  4 A615-40  #6 23'-2"   12  A 23'-2                                   34.8   139.2
 18 A615-40  #6 24'-2"   22  A 24'-2                                   36.3   653.6
  4 A615-40  #6 44'-4"   13  A 44'-4                                   66.6   266.4
128 A615-40  #7 9'-6"    16  K 8'-8" 0'-10                             19.4   2486.4
 33 A615-40  #7 10'-10"  19  Y                                         22.2   731
 33 A615-40  #7 10'-10"  24  Y                                         22.2   731
 29 A615-40  #7 11'-8"   20  Y                                         23.9   691.8
```

Fig. 27 Rebar Schedule Generated from the Model

3.1.5 On-Site: Erection Engineering and Foundation Work

Another benefit of the 3D modeling effort extends to the planning of erection procedures, as animations of erection procedures are straightforward to produce from the 3D model. The final bridge geometry is already "in there," but erection procedure models would require additional information (e.g., swiveling crane models, al-Hussein et al. 2006). The bridge geometry that is not "in there" is that dealing with partially constructed conditions. Such conditions do not necessarily require extra programming – e.g., the user can turn on just those levels of the new bridge CAD model that are erected in place at a given stage of the erection procedure and turn off just those levels of old bridge that have been removed at a given stage (although CAD layer/level standards have traditionally not been used for lifecycle aspects, Howard and Bjork 2006). Alternately, pieces of the bridge could be moved around (in 3D CAD) just like a crane would. Example snapshots of the bridge model of Fig. 11 under construction are shown in Figs. 28 (for a girder spliced on the ground) and 29 (for girders spliced in the erected position).

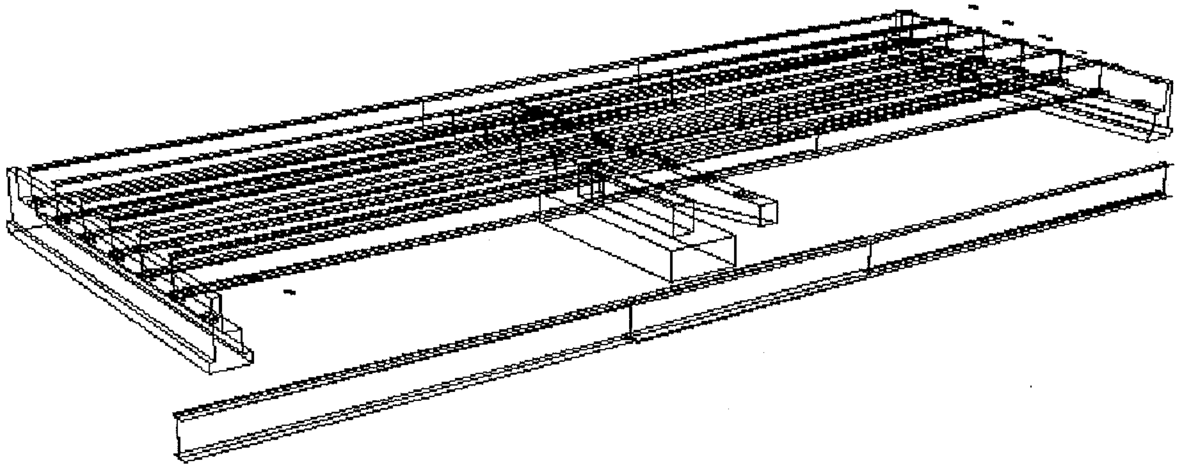

Fig. 28 Use of Model for Erection Procedure Planning (Girder Spliced on Ground)

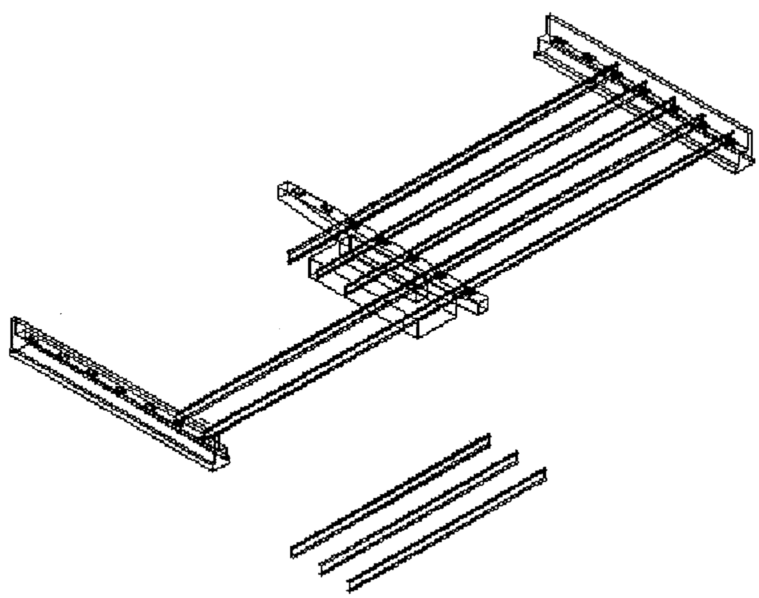

Fig. 29 Use of Model for Erection Procedure Planning (Girders Spliced in the Erected Position)

Erection procedures typically contain the following types of information, some of which go beyond the basic bridge product data that has been the principal focus of this effort:

- Project information: contract number, project id
- Plan of work area: support structure, road, utilities
- Erection sequence for main and secondary members

- Delivery location of each girder
- Location of each crane and each pick
- Lifting weight of each member
- Lift and setting radius for each pick
- Pick point(s) of each member
- Girder tie - down details or other method of stabilizing erected girder
- Bolting requirements when stabilizing members during the erection sequence
- Method and location of temporary support for field splice and curve girder, including shoring, falsework, etc.

Thus, only some of the content in current erection procedure drawings comes from the geometry of the bridge itself. Such information (e.g., pick weights) is easily extractable from the bridge model. But other aspects (e.g., whether crane pads need to be poured in a contemplated crane location to make a crane sufficiently stable to execute a contemplated pick) require erection engineering considerations that are distinct from direct consideration of the bridge model itself – which has been the focus of this project and report. Construction planning, however, is facilitated by access to the 3D model (de Vries and Harink 2006). Appendix A contains a lexicon and views of data needed for fabrication and construction phases as well as design and includes some erection-specific data, highlighting items that are not in the current BridgeWare data model – updating which would require a cumbersome procedure were they to be implemented in BridgeWare. In any case, 3D will bring advantages of its own, e.g., detecting interference between crane booms and overhead wires if such are on-site (and included in the 3D site model!).

Foundation work on site requires data support not only from the substructure data model but also for items such as the following:

- Excavation procedure, protective system
- Procedure: Excavation→engineer approval→pour concrete→engineer approval→backfill
- Measurement: Horizontal limit, top limit, lower limit.
- Pay items: e.g., Excavation, in cubic meters or yds, protective systems, control and remove water, clearing and grubbing, and removal existing structure.

The software used for geometric alignment of the roadway carrying the bridge (e.g., Fig. 4) includes the land surface. We envision the user working down from road (deck)surface and up from foundation keyed to subsurface data. LEAP's IBS software, for example, hooks superstructure analysis to RC-PIER substructure analysis. Excavation (and pay items associated with it) presents additional data requirements summarized above and listed in greater detail in Appendix A (Data Dictionary and Views for Fabrication and Construction Phases), but 3D modeling facilitates additional benefits here as well (Makkonen et al. 2006).

3.2 Accomplishments

The following has been accomplished in the 3D bridge modeling work performed in this project:

- In order to maintain the "single data entry" ideal, incorporated line-girder analyses, including V-load methods for curved bridges, programming using the WSDOT Foundation Libraries,

- Demonstrated the workability of 3D-centric bridge modeling for design through detailing for fabrication for both steel plate girder superstructures and precast prestressed concrete girder superstructures (including strands, stirrups, and deck reinforcing),
- Developed data dictionary for fabrication and construction phases (see Appendix A) and demonstrated export of selected information from the detailed model that would be used automatically and thus leveraged by downstream concerns such as automatic quantity takeoffs for material ordering and management, CNC fabrication, scheduling, and erection procedure development,
- Demonstrated the feasibility of achieving the single-entry ideal to the extent that interoperability challenges could be overcome by direct programming (as implemented herein using Visual Basic programming in the Bentley environment and C++ macro programming in the Tekla Structures environment),
- Demonstrated the feasibility of maintaining the parameters driving the 3D model in conventional database software (Microsoft Access),
- Demonstrated the implementation of file transfer (for interoperability) using XML export and import, in accordance with emerging trends evolving in the industry for electronic data exchange,
- Identified parameter dependencies sufficiently to model typical steel and concrete bridges with a manageable number of parameters, and
- Clarified the remaining requirements needed to transfer the technology to achieve streamlined bridge delivery from it in practice, as documented subsequently.

4. DISCUSSION AND EVALUATION

Although as demonstrated in section 3 many individual pieces of the envisioned workflow are possible today with available software, there are still several key "missing links."

4.1 Case Study

In order to investigate potential deployment issues in actual bridge projects, several actual bridges were modeled as part of this project. In particular, plans for a precast prestressed pretensioned structure carrying Rte 33 in Northampton County, Pennsylvania were provided by PennDOT for our use. This structure was a simple-span bridge superelevated to carry a slight horizontal curvature. Various aspects of the 3D modeling of this structure are illustrated in this report (e.g., Figs. 19 – 21 and Figs. 24 – 27). Although the 3D modeling of this structure (the focus of this project) worked well, the full benefits of it could not be achieved due to current interoperability limitations.

4.2 The Need for Interoperability

Unlike most IDEA projects, our subject here concerns more of a methodology than of a product – AASHTO BridgeWare and commercial software developers could be expected to provide contributing products *if* industry-standard non-proprietary data standards sufficiently robust for the bridge lifecycle were in place. The methodology itself is illustrated particularly in sections 2 and 3 of this report. One premise in the proposal that led to this project was that 3D vs. 2D benefits could be quantified virtually, i.e., off-line – but that proved problematic due to the fact that fabricators and contractors are not currently geared up to work with 3D contract "documents." Another premise was to separate out the 3D modeling aspects (the initially intended focus of this project) from the interoperability aspects, but the work conducted in this project demonstrated that both are needed and are inextricably intertwined.

The problem of interoperability is revealed by asking the question: can other stakeholders use the information without the software? Here was where our own project team effort was stymied. Ultimately, the potential benefits of 3D modeling are not fully leveraged without adequate interoperability [Gallaher et al. 2004].

The interoperability problem is vexing, and it is unsolved. In a conference call with industry participants, it became evident that the most that can reasonably be expected regarding the willingness of software developers to write translators to enable import/export with other applications that are of interest for an integrated bridge delivery workflow is that there be an ***industry-consensus*** standard information format which is ***non-proprietary*** [Suhrawarby 2005]. To such a format they would be willing to invest development resources to export, and from such to import. Of course, that's the rub – there is currently no such format.

A NCHRP-format problem statement to address this issue was developed during the course of this NCHRP-108 project work and is being considered for funding. This statement is included for completeness herein as Appendix B.

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 BrIM 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 [Shirole 93].

Another aspect of interoperability desiderata concerns the transfer of design information (e.g., reactions, load combinations, etc.) from one component to the adjacent superstructure member(s) or to the substructure unit, etc. Commercially available bridge analysis software programs are already moving in this direction of such a more integrated approach. One example is LEAP Software's IBS (Integrated Bridge System) which integrates their previously standalone CONSPAN (superstructure) and RC-PIER (substructure) applications applications through a single database in conjunction with its GEOMATH highway geometry modeler (LEAP 2006). Another example is AASHTOWare with its recently developed substructure data model to complement its reasonably well-established superstructure data model. Such data "handoff" capabilities will be needed to realize the benefits of leveraging upstream information into downstream processes in a manner that avoids time-consuming error-prone manual transcription of data.

Implementing such capabilities will require coordinated effort on a significant scale since the resulting model would have to allow for many variations or choices for the designer, and the model would have to include the deck, the stringers (straight, curved, hybrid), bearings (fixed, expansion, multi-rotational, restrained, etc.), joints as well as perhaps the interaction by the substructure units. This interaction would be required not only for the dead load, live load, wind loads on live live load, superstructure, and the substructure, but ideally also for extreme events such as floods, seismic effects, etc. Fortunately, such a task does not have to start from scratch, since BIM (Building Information Modeling) is receiving significant attention in a similar market (i.e., building construction) that is considerably larger than the bridge market, yet with similar categories of stakeholders. An optimistic view of this situation is that with relatively minor adjustments and by benefiting from their lessons learned, their solutions can be adapted for bridges. The fact that one of the premier seismic analysis applications, SAP2000, has recently developed a bridge analysis module as well as an interface to 3D (Tekla) CAD detailing, suggests that improvements to interoperability can be expected to be forthcoming, albeit proprietary. If such interoperability were based on bridge industry standards for the data exchange which would be facilitated by the work proposed in Appendix B, then the interoperability would not have to be allied to proprietary software package linkages. Avoidance of a proprietary solution is the motivation behind the work proposed in Appendix B.

5. IMPLICATIONS FOR PRACTICE

The vision articulated herein is nothing less than fully integrating design/construction/fabrication of bridges. It will require a fundamental change in business practice by owners (DOTs) to make this work, along with development of software standards that will have to be used across the entire industry. There are also a number of additional technical changes that are needed. It is not just 3D graphics but an integration of all aspects of design and construction. The very workflow of business processes needs to be re-thought.

> "The first rule of technology is that automation applied to an efficient operation will magnify the efficiency. The second is that automation applied to an inefficient operation will magnify the inefficiency." Bill Gates, as quoted in [Davies 2006].

Various issues arise when re-thinking business processes, e.g.,

- Micro issues, e.g., CAD standards (currently presuming 2D) need to be made 3D-ready, with libraries to suit. What is involved in converting them?, and
- Workflow steps, e.g., consider markup and redlining tools in tandem with "change management" mechanisms. While markup tools exist today to enable e-redlining (e.g., of shop drawings), such tools may not be as fully developed for a 3D world, especially one that does not require proprietary software solutions. Other issues arising include those of user training, and having viewers enabling relevant stakeholders to inspect not only the model itself but also others' redlining comments without being required to acquire their own licensed copy of the full-blown 3D modeling software itself in order to do so.
- Macro issues, e.g., construction documentation is not (any longer) fundamentally about drawing production. New questions then arise: ***what*** should be issued, and ***how***? For that matter, how should design firms price their work (since $ per drawing is not longer relevant)?
- Linkage and dependency issues, e.g., traditional CAD standards are more or less strictly graphical (or geometrical) in nature. Are these kinds of CAD standards viable in a brave new world where the 3D bridge information model (BrIM) dynamically linked to associated specifications is the central evolving deliverable, rather than static 2D drawings and separate static specs. Probably not!

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 and their implications for business processes.

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." Appendix C contains the full text of the resolution.

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

5.1 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, although establish ISO standards could also be used (e.g., Lee and Jeong 2006).

It must be noted that, as discussed with Figs. 10 and 11, the data itself is the fundamental driver - the envisioned extraction of data does not depend upon the 3D CAD/CAM model generated from that data. As such, 3D CAD/CAM software should be thought of as just one way of extracting/viewing the data. Additional means of data extraction will be necessary, e.g., database data extraction commands or access via keywords, e.g., names of entities such as those listed in Appendix A. A key challenge, however, will be how to allow unique design solutions (weird stuff) within a standardized digital format. Tekla, for example, allows users in its 3D CAD environment to custom-define "weird stuff," e.g., structural connections for which no connection macros are predefined, in terms of the constituent elements (e.g., plates, bolts, welds) without requiring custom programming by the user. Utilizing this capability in a proprietary 3D CAD environment does mean, however, that the underlying parameterization may not be in terms that would be most natural for subsequent "keyword" based access. Underlying constructs for enabling custom capabilities include "custom objects" (Kramer 2003) and "abstract functional objects" (Sacks et al. 2004).

All these requirements may appear daunting in light of the difficulties inherent in trying to change how an entire industry does business. A smoothly running team, however, 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 BrIM approaches sooner rather than later. Therein lies the principal hope for transferring this technology to deployed practice. Such teams, moreover, are more likely to be assembled within a D/B (Design/Build) project delivery mechanism.

5.2 D/B Mindset vs. D/B/B "Business as Usual" Adversarial Fragmentation

"Who owns the model?" is a question that often arises among individual stakeholders when they first hear about 3D BrIM 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 [2005] 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. Instead of waiting for an entire industry to change, Eastman et al. (2002) conclude that in the fragmented context of the construction industry, IT technology innovation must evolve based on local benefits, not industry-wide ones.

Change management schemes, as described earlier, can be expected and will be needed to provide the mechanisms for one stakeholder to "flag" proposed changes requiring approval from other stakeholders, particularly in a D/B/B environment. Change management schemes are already key parts of CAD application environments such as Bentley ProjectWise, which is currently being adopted in a number of state DOTs. The need for such checks must be balanced against the need for the accelerated delivery enabled by the streamlined data flows. Since no computer software is likely to have a P.E. license in the foreseeable future, it is our opinion that involvement of qualified human users at key junctures in the workflow will prevent a completely automated approach from being deployed. On the other hand, considerable sets of default values and use of wizards should enable data entry to become less tedious. Such developments must eventually occur in the interest of eventual user acceptance. But before they are implemented, robust extensible data modeling must be conducted first. It is unfortunate but apparently unavoidable that determining the appropriate level of automation (or man-machine interaction) may have received insufficient attention in bridge data modeling efforts to date. It is certainly desirable not to reduce engineers to the role of data-entry clerks, since a practical result of robust

3D BrIM software and workflows ought to be to free up engineers for more creative work that only humans can do in exploring a wider set of options for a given bridge crossing.

5.3 Re-Shaping of Stakeholder Roles

The design drawings (or, rather, the underlying model which automatically generates the design drawings) must also be accurate for this concept to work – if it is that entirely unaugmented model that is also used for fabrication and construction. If the construction contractor's subs augment the model they inherit from the designer with their own shop-specific and construction-specific details, however (e. g., cut cambers that are different than final dead-load cambers in the design model), then there is still no problem – no one is requiring the designer to specify cut-cambers. Another way to state the point is to say that the model produced by the designer, and the QA/QC protocols used to generate that model, must provide a sufficient basis to build from the model, not just to bid from it (as stated in sections 3.1.2 and 4.2). Thus, drawing dimensions cannot be "fudged;" dimensional changes must always be made to the originating model since drawings are only reports extracted from that model. Thus, detailed completeness and accuracy of the model is of paramount importance when the model progresses to the point where it is being used to drive fabrication and construction. But "design drawings," as the term is currently understood, would still not necessarily contain all the information in such a model.

In any case, in the envisioned 3D BrIM 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 [AISC 2005]. 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., [Carrato and Holland 2004]), and concrete (e.g., [Sacks et al. 2004]).

6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary and Conclusions

In the project documented in this report, a future is envisioned for the accelerated delivery of bridges, and a solution delivering several key parts of that future is implemented, 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-BrIM based collaborative ways of doing business are needed to transfer the results fully to highway practice.

6.2 Recommended Phase 2 Development

The ideal situation for further development would have all of the following in addition to the items listed as "Implications for Practice" in Section 5 above:

- A carefully devised level playing-field shoot-out of 2D vs. 3D BrIM,
- Ability to work out the kinks off-line prior to deployment on a real bridge project in real-time, and
- All participants fully "up the learning curve" not just in new software usage but also in needed standards practices and changes to usual workflows resulting from the brave new world of a model-centric (rather than drawing-centric) approach.

Phase 2 development, unfortunately, will not have the luxury of having all of the above desiderata in place. It is our opinion that the least undesirable situation for further development would be a design/build setting where, e.g., several dozen "routine" bridges on a stretch of highway on a given contract could be developed using 3D BrIM "off-line" but in parallel with conventional processes, where the designer delivers the design model in 3D detailing software format (which in turn is sufficiently robust to export construction information directly). Prior to this, of course, the project team would need to have hammered out its own team "bridge language" standard that is sufficiently robust to support each of the tasks that each of the stakeholders is responsible to carry out on those bridges.

Off-line it will be necessary to hammer out the changes in workflows and accompanying standards practices. Also, "single-entry" requires a moderated data vault. The role and responsibilities of the model manager stakeholder are yet to be hammered out in the project team – difficult to do when each project team is a different "pick-up softball team"! What is needed is repeated passes, through various projects, of the same project team (presumably D/B) as the first step. But what such project team has the luxury of sinking time into off-line effort like that? Thus, phase 2 development will need to include the "virtual" development of team-wide workflow changes and accompanying standards practices.

As for the constituting of a level-playing-field 2D vs. 3D comparison, more careful planning is needed. What, in fact, would be required, to compare 2D to 3D project delivery on a "level playing field"? In order to compare a bridge project delivered using familiar 2D approaches to one delivered using a 3D "single model based" approach, the following desiderata come to mind:

- Training of each stakeholder participant such that each is as comfortable with 3D as they are with 2D.
- Solving of the interoperability issues (which is not a short-term prospect) or side-stepping them on a project-specific basis, e.g., by requiring the designer to deliver the designs using 3D CAD detailing software that is sufficiently robust not only for the detailer to augment directly but also sufficiently robust to export electronic content in formats needed for downstream applications such as scheduling/material management, costing, and transportation (etc.).
- Extending beyond 3D (product model focus) to include 4D (process model aspects).
- There is a need for a principled development of a test suite of steel and concrete bridge projects that is considered to be sufficiently representative by all stakeholders. This test suite could then subsequently be made available for pilot studies aimed to furthering the use of integrated processes based around shared 3D/4D CAD and product models of the bridge structures. Further thoughts on development of such a test suite are provided in Appendix D.

There certainly is further insight to be gained from other industries that have benefited from Product Lifecycle Management (PLM) (Williams 2005). A definition of PLM (Product Lifecycle Management) has been given as follows:

> "Product Lifecycle Management (PLM) systems support the management of a portfolio of products, processes and services from initial concept, through design, launch, production and use to final disposal. They co-ordinate products, project and process information throughout new product introduction, production, service and retirement among the various players, internal and external to the OEM, who must collaborate to bring the concept to fruition.
>
> The system maintains a vault, which may be physically distributed, but has a single logical index to all the documents containing product, project and process information. PLM applications use workflow and authorisation rules to give orderly access to this vault's information. The various processes of new product introduction, production, service and retirement use a single source of product information [Evans 2006]."

In addition to CAD/CAM software tools, such applications have been deployed with subsystems [Evans 2006], which have clear analogs in the bridge industry, such as the following:

- Technical Document Management (e.g., spec sheets, process plans, work instructions – with appropriate mechanisms for index and access),
- Virtual Mock-Up (i.e., visualization to check fitness for purpose, interferences, etc),
- Release Authorization and Engineering Change Control Systems (tracking status of requested changes and the other parts affected by such changes),
- Mechanical Computer-Aided Engineering (i.e., behavior simulation of stresses, vibrations and other structural analysis of interest at conceivably different stages of fabrication and construction),
- Maintenance, Repair, and Operations (e.g., records of as-built and as-maintained products along with maintenance and repair processes carried out),

- Project and Program Management Systems (i.e., monitored resources used to perform the development tasks and their inter-relationships with schedules and deadlines as well as risks and contingency plans, and
- Computer-Aided Production Engineering (e.g., modeling the fabrication process and/or work cell layout to simulate fabrication and erection processes in order to generate efficient fabrication and erection procedures and to train operators).

Thus, Phase 2 development should also survey recent lessons learned from related industries applying PLM.

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Appendix A

Data Dictionary and Views
for
Fabrication and Construction Phases

Entity	Attribute	Description	Designer	Fabricator	Erector	QA/QC/Owner
beam_def	***Defines geometric and material properties of a beam***					
	beam_projection_start	length of beam definition not modeled at the start of the member	▲		△	△
	beam_project_end	length of beam definition not modeled at the end of the member	▲		△	△
	impact_factor_adjustment_beam		▲		△	
	haunch_embedded_flng_ind	indicate if the flange is embedded in the haunch	▲		△	△
beam_hinge_loc	***Defines the location of beam hinges***					
	hinge_loc_id	id of hinge location	▲		△	△
	dist_hinge	distance from beginning of beam to the hinge	▲		△	△
bearing_def	***Defines configuration, geometric properties, and material properties of a bearing supporting a member***					
	bearing_def_id	the id for a bearing definition	▲		△	△
	bearing_type	the type of bearing	▲		△	
	bearing_name	name of bearing	▲		△	
bending	***Define the bending procedure in shop factory***					
	fracture_critical_ind	check whether the material is fracture critical or not		▲		
	bending_radius	the rolled radius when bending		▲		
	roll_direction	the direction of rolling		▲		
blast_cleaning	***Defines the shop blast cleaning procedure of steel members***					
	abrasive_type	the type of abrasive used in blast cleaning		▲		
bolt_def	***Defines bolts usded in bridge structures***					
	bolt_def_id	the id of a bolt definition	▲	△	△	
	bolt_name	name of bolt	△	△		
	bolt_designation	bolt designation	▲	△		
	bolt_diameter	bolt diameter	△	△	△	
	hole_diameter	hole diameter	△	△		
	lrfd_min_tensile_strength	LRFD minimum tensile strength	△	△		
	lrfd_required_tension	LRFD required tension	△	△		
	exclude_threads_ind	indicate whether or not to exclude threads	▲	△	△	
bolt_holes	***Defines punching or drilling holes procedure in shop factory***					
	diameter_plus	define the difference between the hole diameter and bolt diameter		▲		
	full_size_ind	indicate whether the hole should be drilled or punched full-size while in assembly		▲	△	
	accuracy_requirement	allowed positive tolerance of holes		△	△	△
	group_accuracy_before_reaming	the accuracy of hole group before reaming		▲	△	△

Entity	Attribute	Description	Designer	Fabricator	Erector	QA/QC/Owner
	group_accuracy_after_reaming	the accuracy of hole group after reaming		▲	△	△
bridge_bolt_field	***Defines a bolt field***					
	bolt_field_id	the id of bridge-defined bolt field	▲	△	△	
	bolt_field_name	the name of bridge-defined bolt field	▲	△	△	
	center_gage	distance between the 2 center gage lines		▲	△	
	center_pitch	distance between the 2 center pitch lines		▲	△	
	gage	distance between adjacent lines of bolts		▲	△	
	num_gage_lines	number of gage lines		▲	△	
	num_pitch_lines	number of pitch lines		▲	△	
	pitch	distance along the line of principlal stress between centers of adjacent bolts, measured along the bolt line		▲	△	
	staggered_ind	indicates if the bolts are in uniform lines or staggered		▲	△	
	symmetrical_gage_lines_ind	indicates if the gage lines are symmetric about the centerline of the connection		▲	△	
	symmetrical_pitch_lines_ind	indicates if the pitch lines are symmetric about the centerline of the connection		▲	△	
chemical_properties	***Chemical properties of the material showed in the mill test report***					
	chemical_element	chemical element			△	△
	element_measured_value	measured value of the chemical element			△	△
cold_bending	***Defines the cold bending procedure in shop factory***					
	load_point	load points when cold bending steel		▲		
crane_details	***Defines the cranes used in erecting the bridge member in field***					
	crane_model	model of the crane			△	
	crane_name	name of the crane			△	
	crane_num	the number of cranes used in erection			▲	△
crane_loc	***Defines the loaction of cranes when hoist bridge members***					
	position_num	the number of positions where the cranes work			▲	
	crane_loc	the location where the crane work			▲	
	dir_of_boom_swing	direction of swing of the crane boom			▲	
	max_boom_radius	maximum radius of the crane boom			△	
	outrigger_loc	the location of the crane outrigger			▲	
	support_mats_loc	the location of the support mats			▲	
crane_chart	***Defines the features of the cranes***					
	crane_chart_num	the number of the crane capability chart			△	
	capacity_overside	the largest weight that a crane can hoist			△	

Entity	Attribute	Description	Designer	Fabricator	Erector	QA/QC/Owner
	counter_weight	the weight of the counter			△	
	counter_weight_loc	the location of the counter			△	
conc_beam_def	***Defines the geometry and material properties of a concrete beam***					
CVN_toughness	***Defines the CVN test report of mill material***					
	min_absorbed_energy	minimum absorbed energy		△		△
	test_temperature	test temperature		△		△
diaph_loc	***Defines geometric and material properties of a diaphragm***					
	diaph_loc_id	id for a diaphragm location	▲	△	△	△
	left_spng_mbr_dist	distance to nearest member to the left		▲	△	
	right_spng_mbr_dist	distance to nearest member to the right		▲	△	
	num_spaces	number of spaces	▲		△	
	spacing	diaphragm spacing	▲		△	
	diaph_weight	weight of a diaphragm		▲	△	△
engineer_approaval	***Defines the procedure of engineer approval in project phases***					
	engineer_approval_id	the id of the engineer approval		△	△	▲
	approve_date	the date when the request is submitted		△	△	▲
	other_comment	the comment in the approval		△	△	▲
	submit_date	the date when the request is approved		△	△	▲
friction_sawing	***Defines the procedure of friction sawing***					
	blade_type	bandsaw blade type		▲		
	blade_diameter	diameter of the blade		▲		
	rotate_speed	the rotation speed of the fly		▲		
girder_mbr	***Defines location specification information of a girder***					
	horziontal_curve_ind	indicate whether girder has horizontal curve or not	▲	△	△	
girder_stability	***Defines the detaiols related to erection stability***					
	detail_num	the number of erection detail			▲	△
	anchorage_details	the detail of anchorage in erection			▲	△
	clamp_details	the detail of clamps in erection			▲	△
	hook_details	the detail of hooks in erection			▲	△
	num_of_tie_downs	number of ties in erection			▲	△
	temporary_erection_supports	detail temporary support in erection			▲	△
	tie_down_cable_angle	the angle between the cable and erected members			▲	△
hand_cleaning	***Defines the procedure of surface cleaning by hand***					
	hand_cleaning_tools	the tools used in hand cleaning		▲		
hot_bending	***Defines the procedure of hot bending***					
	bending_temperature	temperature when bending		▲		

Entity	Attribute	Description	Designer	Fabricator	Erector	QA/QC/Owner
inspection_procedure	***The inspection record***					
	inspection_procudure	the inspection record or test report		△	△	▲
mag_particle_testing	***Defines the contents in the magnetic particle testing report***					
mark_system	***Defines the marking system by fabricator***					
	assembly_mark	the mark of sub-assembly		▲	△	△
mbr_conn_def	***Defines geometrical and materal properties of a connection***					
	mbr_conn_def_id	id of a connection definition	▲	△	△	
mbr_conn_location	***Defines the location of connections***					
	mbr_conn_id	id for a connection	▲	△	△	
	frame_ind	indicates if a member is framed into other members or is supported from below by another member	▲		△	
	vert_dist	vertical distance between two framed members	▲		△	
mill_bolt	***Defines the bolt list that purchased by the mill***					
mill_order	***Defines the mill order detail***					
	arrive_date	arrival date of the item		▲		
	item_quantity	quantity of an ordered item		▲		△
	items_id	id for an item in a mill order		▲		△
	mill_order_id	id of a mill order		▲		△
	order_date	order date		▲		
mill_plate	***Defines the steel plate that purchased by the mill factory***					
	length_mill_plate	length of a mill plate		▲		
	width_mill_plate	width of a mill plate		▲		
	thickness_mill_plate	thickness of a mill plate		▲		
	plate_nesting_detail	optimize the plate cutting		▲		
	plate_grade	steel grade of the mill plate		▲		
mill_rolled_shape	***Defines the steel rolled shape that purchased by the mill factory***					
	mill_shape_length	length of the mill steel rolled shape		▲		
	shape_nesting_detail	optimized layout for cutting mill shape to several shape members		▲		
	shape_grade	steel grade of the mill rolled shape		▲		
mill_test_report	***Defines the contents in mill test report***					
	certificate_date	certificate date of the report		△		△
	certificated_by	certificate party of the report		△		△
non_destructive_test	***Defines the contents in the non-destructive test***					
notice_of_fabrication	***Notice of fabrication isssued by the fabricator***					
	fabrication_start_date	the beginning date of fabrication		▲		△
	notice_date	the date of notice		▲		△

Entity	Attribute	Description	Designer	Fabricator	Erector	QA/QC/Owner
notice_of_painting	***Notice of painting by the fabricator***					
	days_advance	days advaced before painting starts		▲		△
notice_of_work	***Defines the notice of work***					
	notice_id	the id of notice		▲/△	△/▲	△
oxygen cutting	***Defines the procedure of oxygen cutting***					
	guided_type	indicate whether hand-guided or mechanically guided		▲		
	flame_temperature	temperature of the flame		▲		
	fuel_gas_type	the type of fuel used in oxygen cutting		▲		
	work_pressure	work pressure in cutting		▲		
	cutting_speed	cutting speed		▲		
	cutting_width	the width of steel that will be removed		▲		
painting_approval	***Defines the contents in painting approval***					
	painting_approval_id	the id of painting approval		▲		△
	atmospheric_condition_control	control of atmospheric condition		▲		△
	surface_preparation_change	indicate if the surface preparation has some changes		▲		△
painting_def	***Defines the painting process***					
	painting_spec	painting specification		▲		
	allowed_work_temperature	allowed temperature range when painting		▲		
	coating_system	coating system		▲		
	paint_color	color of paint		▲		
	paint_type	type of paint used on steel members		▲		
	painting_tool	tools used in painting		▲		
	cure_method	cure method after painting		▲		
	cure_time	cure time after painting		▲		
penetrant_testing	***Define dye penetrant test procedure***					
pick_weight_table	***Table includes the weight of assembles that will be erected in the field***					
	pick_weight_table_num	number of the weight table			▲	
	assemble_mark	mark of the assemble		▲	△	
	assmbe_weight	weight of the assemble		▲	△	
	rigging_weight	the weight of rigging			▲	
	total_weight_of_lift	the total weight in the lift			▲	
	weight_of_attachment	the weight of attachment			▲	
producer	***Table includes all the information of material producers***					
	producer_id	id of the producer		▲		
	producer_name	name of the producer		▲		
	producer_addr	address of the producer		▲		

Entity	Attribute	Description	Designer	Fabricator	Erector	QA/QC/Owner
	producer_phone	contact phone of the producer		▲		
shear_connector	***Table to store bridge-defined shear connector definitions***					
	shear_connector_id	the id of a shear connector	▲	△	△	
	stud_diameter	diameter of stud	▲		△	
	stud_height	height of stud	▲		△	
	channel_length	length of channel	▲		△	
	lrfd_nominal_shear_resistance	nominal LRFD shear resistance	▲			
	lrfd_fatigue_resistance	LRFD fatigue resistance	▲			
	stud_name	name of stud	▲			
shear_conn_stud_field	***A field of steel studs which transfer shear stresses between a spanning member and concrete deck***					
	dist_flng_edge	distance from the edge of the flange plate to the edge of the stud connector	▲		△	
	long_spacing	spacing of the stud rows measured along the length of the beam	▲		△	
	num_of_studs	number of studs in a row	▲		△	
	num_rows	number of rows of studs in the range	▲		△	
	stud_dia	stud diameter	▲		△	
	stud_hgt	stud height	▲		△	
	trans_spacing	spacing between studs across flange	▲		△	
shear_conn_field	***A field of components which transfer shear stresses between a spanning member and concrete deck***					
	shear_conn_id	id for a range of shear connectors on a beam	▲		△	
	dist_btwn_mbrstrt_and_connstrt	distance from the beginning of a member to the beginning of a range of shear connectors	▲		△	
	length_of_conn_range	the length of beam over which the shear connector range extends	▲		△	
shop_assembly_details	***Details about shop assembly***					
	shop_assembly_procedure	Define the procedure of shop assembly		▲		
	match_marking_scheme	the match scheme that put the right member together		▲		
shop_cleaning_and_painting	***Defines cleaning and painting procedure in shop factory***					
	cleaning_painting_procedure	id for cleaning and painting procedure		▲		
skew	***Define the skew angle of bridge***					
	skew_angle_to_baseline	the skew angle to the girder line	▲			
solvent_cleaning	***Define procedure of solvent cleaning***					
spng_mbr_def	***Defines physical and geometrical definition of a bridge member***					
	spng_mbr_def_id	the id of a member definition	▲	△	△	

Entity	Attribute	Description	Designer	Fabricator	Erector	QA/QC/Owner
	additional_self_weight	additional weight per unit length of member	▲		△	
	conn_self_weight_percent	percent of member dead load to be applied as additional load due to connection weight	▲		△	
splice_bolt_field	***Defines bolt field in beam splice***					
standard_fabrication	***Defines standard fabrication process in shop factory***					
	fabrication_procedure	fabrication procedure		▲		△
	fabrication_date	fabricate date		▲		△
steam_cleaning	***Define the procedure of steam cleaning***					
	detergent_type	detergent used in surface cleaning		▲		
	steam_cleaning_time_limit	the time requirement in steam cleaning		▲		
stl_angle_conn	***Defines relative position of two angles used to connect a web and a flange***					
	angle_leg_ind	indicates whether the long leg of angle attached to the web		▲		
	angle_length	length of the angle to connect a web plate and flange plate		▲		
	angle_position_ind	indicates if the angles are used to attach the top flange or the bottom flange		▲		
	angle_y_offset	vertical offset to the angle relative to web measured from edge of web to back of angle		▲		
stl_beam_def	***Defines the material and geometrical properties of a steel beam***					
stl_beam_assembly	***Locates steel component defining geometric and material properties along a steel beam***					
	stl_beam_assembly_id	the id of a steel beam assembly		▲	△	
	stl_beam_assembly_dist	distance from beginning of member to the steel component		▲	△	
stl_beam_segment	***Define the beam segment that assembled in shop factory***					
stl_bearing_stiff_loc	***Defines location of bearing stiffeners for a steel beam***					
	bearing_stiff_loc_id	the id of bearing stiffener location	▲	△		
	dist_from_support	distant from support	▲		△	
	support_num	support number	▲		△	
stl_component	***Defines geometric and material properties of steel plates and rolled shape***					
	stl_component_id	id for a steel component	▲	△	△	
	name	name of steel component	▲	△	△	
	stl_componet_mark	fabricator's mark for steel beam component		▲	△	
stl_cover_plate	***Defines dimensions and relative location of steel plate used as a cover plate***					

Entity	Attribute	Description	Designer	Fabricator	Erector	QA/QC/Owner
	length_cover_pl	length of cover plate	▲	△		
	num_bolts_cover_pl	number of connection bolts	▲	△	△	
	weight_cover_pl	weight of cover plate	▲	△		
	width_end_cover_pl	cover plate width at the end of the cover plate	▲	△		
	width_start_cover_pl	cover plate width at the start of the cover plate	▲	△		
	relative_pos	relative vertical position of cover plate at start of plate	▲	△	△	
stl_cutting	***Defines the procedure to cut steel plate or steel rolled shape***					
	cutting_edge	the dimension from the cutting start point to the edge of the mill plate or rolled shape		▲		
	surface_roughness	the allowed surface roughness		▲		△
	allowed_tolerances	allowed tolerance of the member		△		
	dimension_tolerance	length or width tolerance in cutting		▲		△
stl_flng_plate	***Defines dimensions and relative location of steel plate used as a flange plate***					
	length_flng_pl	length of the flange plate	▲	△		
	top_location_ind	indicates if the flange is top or bottom	▲	△		
	weight_flng_pl	weight of the flange plate	▲	△		
	width_end_flng_pl	width at the end of the flange plate	▲	△		
	width_start_flng_pl	width at the start of the flange plate	▲	△		
stl_general_plate	***Defines dimensions and relative location of steel plate used as a general plate***					
	length_gen_pl	length of the plate	▲	△		
	weight_general_pl	plate weight	▲	△		
	width_end	width at the end of the plate	▲	△		
	width_start	width at the start of the plate	▲	△		
	y_offset_gen_pl	the y offset of center of gravity of the plate from longitudinal axis of the built-up section	▲		△	
	z_offset_gen_pl	the z offset of center of gravity of the plate from longitudinal axis of the built-up section	▲		△	
stl_long_stiff	***Define dimension and relative position of longitudinal stiffeners***					
	length_long_stiff	length of the longitudinal stiffener	▲	△		
	vert_dist_long_stiff	distance from top of web to centroid of steel longitudinal stiffener plate	▲	△		
	vert_dist_by_web_fraction	vertical distance from the top of the web to the center of the longitudinal stiffener plate	▲	△		
stl_long_stiff_pl	***Defines dimension of steel plate used as longitudinal stiffeners***					
	long_stiff_pl_id	id of steel plate used as longitudinal stiffener	▲	△		

Entity	**Attribute**	Description	Designer	Fabricator	Erector	QA/QC/Owner
	material_mark_long_stiff_pl	fabricator's mark for steel plate used as longitudinal stiffeners		▲		
	thick_long_stiff	thickness of the longitudinal stiffener plate	▲	△		
	width_long_stiff	width of the longitudinal stiffener plate	▲	△		
stl_plate	***Defines dimension properties of steel plate***					
	plate_thick	plate thickness	▲	△		
stl_plate_ibeam_def	***Defines the material and geometrical properties of a steel I beam***					
stl_rolled_ibeam_def	***Defines the material and geometrical properties of a steel rolled shape beam***					
stl_rolled_shape	***Defines dimension properties of steel rolled shape***					
stl_section_property	***Defines section properties of prismatic steel area***					
	length	the length of beamhaving these section properties	▲			
	x_offset	the direction offset in the x direction	▲			
	y_offset	the direction offset in the y direction	▲			
	area_gross	the gross cross-sectional area of the section	▲			
	moi_y	moment of inertia of the section about y axis	▲			
	moi_z	moment of inertia of the section about z axis	▲			
	c	the distance from neutral axis to top or bottom fiber, whichever is greater	▲			
stl_splice_def	***Defines geometrical and material properties of steel splice***					
	stl_splice_def_id	the id of a splice definition	▲	△	△	
	web_clear_dist	clear distance between inner edge of flange and web splice plate	▲	△		
	web_end_dist	distance from end of web splice plates to center line of nearest bolt in the direction of gage line	▲	△		
	min_splice_dist	minimum spacing between two splices	▲			
stl_splice_loc	***Locates a steel splice definition along a steel beam***					
	splice_id	id for a splice	▲		△	
	dist_splice	distance from the beginning of beam to the splice	▲		△	
stl_trans_stiff	***Defines transverse stiffener properties for a steel beam***					
	trans_stiff_mark	fabricator's mark for a transvese stiffener		▲	△	
	bearing_stiff_ind	indicate whether the stiffener is a bearing stiffener	▲	△	△	
	num_sides	indicates whether the stiffener is single-sided or double-sided	▲	△	△	

Entity	Attribute	Description	Designer	Fabricator	Erector	QA/QC/Owner
	diaph_stiff_ind	indicates whether a diaphragm is connected on the stiffener	▲	△	△	
stl_trans_stiff_angle	***Defines angle used as transverse stiffener***					
	dist_from_bot_flng	the distance the stiffener angle ends from the bottom flange		▲		
	dist_from_top_flng	the distance the stiffener angel begins from the top flange		▲		
	short_leg_att_ind_trans_ang	indicates which leg is not attached to the web plate		▲		
	vertical_direction_ind	indicates if the transverse stiffener angle is in vertical direction		▲		
	weight_trans_stiff_angle	weight of transverse stiffener angle		▲		
	dist_bot_bolt	the distance from the bottom to the last bolt		▲		
	dist_top_bolt	the distance from the top to the first bolt		▲		
	num_bolts	the num of bolts that attach to the web		▲		
stl_trans_stiff_gnrl_range	***Location of steel stiffener range which describes the max distance between stiffeners with in a range of the steel beam***					
	range_start_dist	distance along beam to start of range	▲	△		
	length_range	length of range to defining stiffeners	▲	△		
	max_spacing	maximum spacing of stiffeners within range	▲			
stl_trans_stiff_loc_range	***Location of steel stiffeners or group of stiffeners along steel beam***					
	trans_stiff_range_id	id of location	▲	△	△	
	num_of_stiff	The number of stiffeners of the above spacing	▲		△	
	spacing_trans_stiff	Spacing of the transverse stiffeners along the beam	▲		△	
	start_dist	Distance along beam where first stiffener of group is located measured at center of stiffener plate	▲		△	
stl_trans_stiff_plate	***Defines plate used as transverse stiffener***					
	dist_from_bot_flng_trans_pl	distance from the bottom flange where the transverse stiffener ends		▲		
	dist_from_top_flng_trans_pl	distance from the top flange where the transverse stiffener starts		▲		
	ins_clip_horz_length_bot	horizontal dimension of the diagonal clip of the stiffener plate adjacent to the juncture of the bottom flange plate and the web plate to allow for the flange to web weld		▲		

Entity	Attribute	Description	Designer	Fabricator	Erector	QA/QC/Owner
	ins_clip_horz_length_top	horizontal dimension of the diagonal clip of the stiffener plate adjacent to the juncture of the top flange plate and the web plate to allow for the flange to web weld		▲		
	ins_clip_vert_length_bot	vertical dimension of the diagonal clip of the stiffener plate adjacent to the juncture of the bottom flange plate and the web plate to allow for the flange to web weld		▲		
	ins_clip_vert_length_top	vertical dimension of the diagonal clip of the stiffener plate adjacent to the juncture of the top flange plate and the web plate to allow for the flange to web weld		▲		
	out_clip_length_bot	the length of the bottom outside clip		▲		
	out_clip_length_top	the length of the top outside clip		▲		
	thickness_trans_pl	transverse stiffener plate thickness		▲		
	weight_trans_stiff_pl	weight of transverse stiffener plate		▲		
	width_trans_pl	width of transverse stiffener plate		▲		
stl_web_cover_plate	***Defines dimensions of steel plate used as a web cover plate***					
	depth_end_web_cover	depth at the end of the web cover plate	▲	△		
	depth_start_web_cover	depth at the start of the web cover plate	▲	△		
	length_web_cover	length of web cover plate	▲	△		
	relative_position	relative horizontal position of cover plate at start of plate	▲		△	
stl_web_plate	***Defines dimensions of steel plate used as a web plate***					
	length_web_pl	length of web plate	▲	△		
	depth_start_web_pl	depth at the start of web plate	▲	△		
	depth_end_web_pl	depth at the end of the web plate	▲	△		
	weight_web_pl	weight of the web plate	▲	△		
straightening	***Defines straightening procedure in shop factory***					
	localized_heat	define the part that need heat to straighten		▲		
	temperature_of_area	the temperature of the heated area		▲		
struct_def	***Definition of a structure***					
	struct_def_id	the id for a structure definition	▲	△	△	
sub_struct_def	***Definition of a substructure***					
super_struct_diaph_mbr	***Locates diaphragm between superstructure spanning members***					

Entity	Attribute	Description	Designer	Fabricator	Erector	QA/QC/Owner
	left_spng_mbr_dist_diaph	distance along the left superstructure spanning member from the beginning of the member ot the diaphragm or brace location	▲	△	△	
	right_spng_mbr_dist_diaph	distance along the right superstructure spanning member from the beginning of the member ot the diaphragm or brace location	▲	△	△	
super_struct_def	***Definition of a superstructure***					
	average_humidity	average humidity	▲			
	num_spans	the number of spans in the superstructure	▲	△	△	
	super_struct_sevice_life	the service life of superstructure	▲			△
super_struct_mbr	***Structural member of a superstructure***					
	super_struct_mbr_id	the id of a member in the superstructure definition	▲	△	△	
super_struct_mbr_span	***Locates spans along a superstructure spanning member***					
	span_id	the id of a span	▲	△	△	
	length_span	the length of the span	▲	△	△	
	dist_span	the distance to the span from the bridge reference point	▲	△	△	
super_struct_spng_mbr	***Locates and defines location specific properties of a superstructure member***					
super_struct_windbrac_mbr	***Locates horizontal wind bracing between superstructure spanning members***					
	brac_spacing	the crossframe spacing	▲		△	
	left_mbr_dist_1	distance along the left superstructure member from the beginning of the member to the first brace location of the crossframe bay	▲		△	
	left_mbr_dist_2	distance along the left superstructure member from the beginning of the member to the second brace location of the crossframe bay	▲		△	
	num	the number of crossframe bays at a specified spacing	▲		△	
	right_mbr_dist_1	distance along the right superstructure member from the beginning of the member to the first brace location of the crossframe bay	▲		△	
	right_mbr_dist_2	distance along the right superstructure member from the beginning of the member to the second brace location of the crossframe bay	▲		△	
support	***Defines support conditions of a superstructure spanning member***					
	support_id	the id for a support defintion	▲		△	

Entity	Attribute	Description	Designer	Fabricator	Erector	QA/QC/Owner
	offset_from_bearing	offset from bearing reference line and member reference line along beam reference line	▲		△	
support_line	***A line locating support points of a superstructure***					
	frame_conn_ind	indicate whether this is a frame connection	▲		△	
	support_line_id	the id of a support line	▲		△	
surface_preparation	***Defines the procedure of surface preparation***					
	surface_cleaning_spec	specification of surface preparation		▲		△
	surface_requirement	the requested surface		△		△
	surface_condition	current surface condition description		▲		
tensile_test	***Description of tensile test report***					
	density	density of material		△		△
	mod_of_elast	modulus of elastic		△		△
	tens_strength	tensile strength		△		△
	thermal_exp_coefficient	coefficient of thermal expansion		△		△
	toughness	toughness		△		△
	yield_strength	yield strength		△		△
transportation_detail	***Describes the shipping method and schedule***					
	transportation_procedure	procedure of shipping		▲		
	dead_load_plus_impact_stresses	the impact of self dead load		▲		
	member_support_location	the location of supports when ship bridge members		▲		
	tie_down_location	the position to tie the ship members		▲		
	tie_down_type	the type of tie		▲		
web_camber	***Defines the dimension change of web due to dead load***					
	bottom_dimensions	bottom dimension of the web plate		▲		
	camber_ordinate	camber ordinates relative to a baseline		▲		
	camber_point_id	id for the camber point		▲		
	dead_load_deflect_concrete	deflection due to the concrete dead load		▲		
	dead_load_deflect_steel	deflection due to the steel part dead load		▲		
	dead_load_deflect_superimposed	deflection due to the superimposed dead load		▲		
	left_end_cut	left end cut relative to the baseline		▲		
	right_end_cut	right end cut relative to the baseline		▲		
	spacing_camber_ordinate	the spacing of the camber ordinates		▲		
	top_dimensions	top dimension of the web plate		▲		
weld_def	***Bridge-defined weld definition***					
	weld_id	the id for a weld definition	▲	△	△	
	ambient_temperature	the environmental temperature		▲	△	
	fatigue_stress_category	the type of fatigue stress	▲			

Entity	**Attribute**	Description	Designer	Fabricator	Erector	QA/QC/Owner
	tensile_strength	tensile strength of weld material		▲	△	
	weld_size	weld size	▲	△	△	
	weld_classification	weld type		▲	△	
	weld_name	name of weld	▲	△	△	
weld_process	***Defines the weld procedure***					
	amperage	electrical flow used in welding				
	filler_metal_diameter	diameter of filler metal				
	filler_metal_type	type of filler metal				
	flux_type	type of flux				
	gas_dew_pt					
	gas_flow_rate	flow rate of gas				
	molding_shoe_type					
	oscillation					
	shielding_type					
	vertical_travel_speed					
	voltage_polarity					
	voltage_type					

Legend

▲ Indicates the attribute is generated by the stakeholder

△ Indicates the attribute is shared by the stakeholder

If there is no "▲"in the row of an attribute, it means this attribute is created by other stakeholders besides the Owner, Designer, Fabricator and Erector.

The Bold Italic part is the description of the Entity.

Items such as diaphragm, bearing, wind brace, and some fabrication processes are anticipated to need further definition.

Entity Directly from Virtis/Opis Database, only those attributes related to fabrication and erection are shown in the Entity

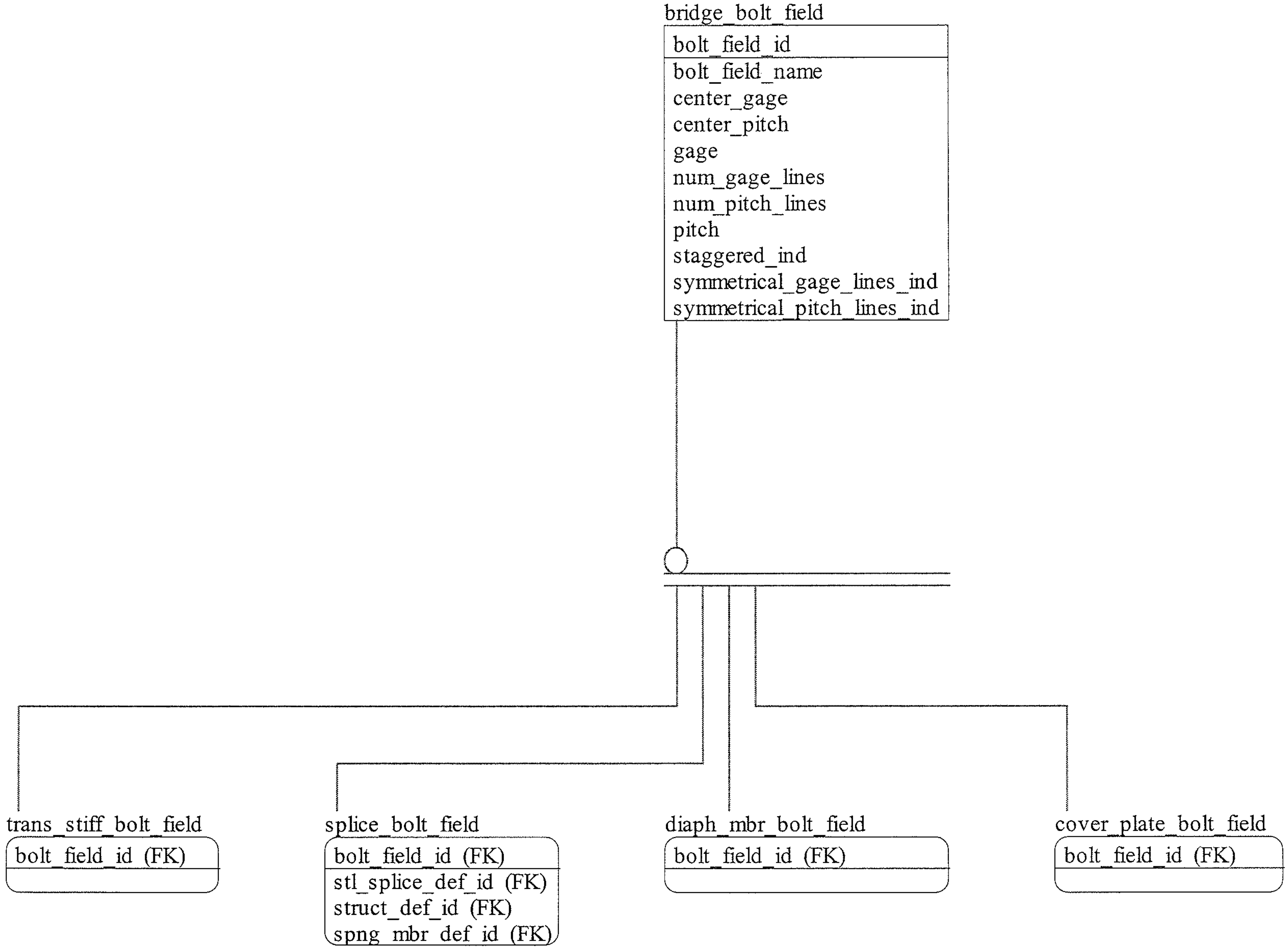
Entity from Virtis/Opis Database, but some attributes are modified or added

New Entity

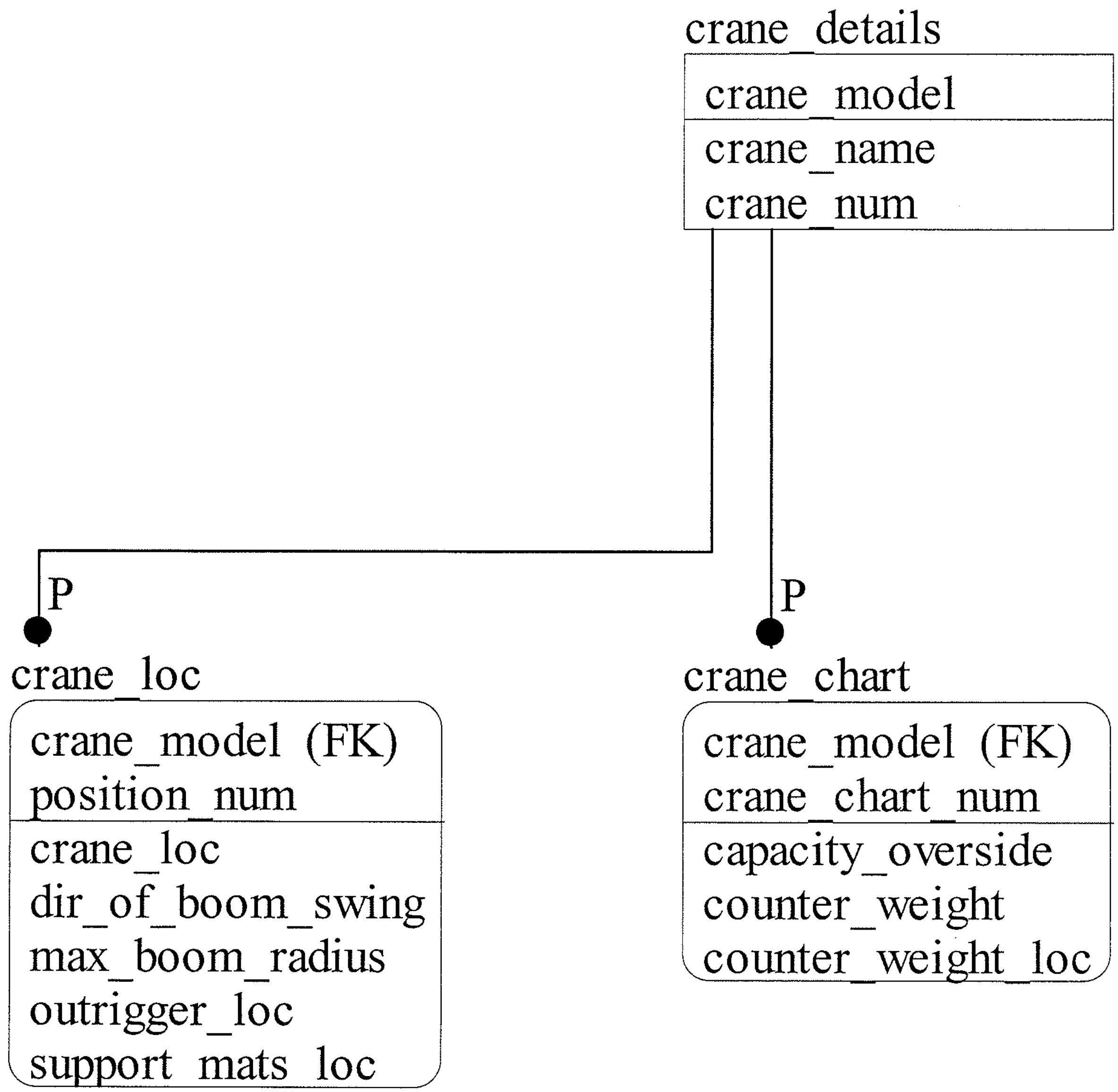
Work in progress:

Field Assembly (bolting splice, diaphragm, wind brace and bearing)

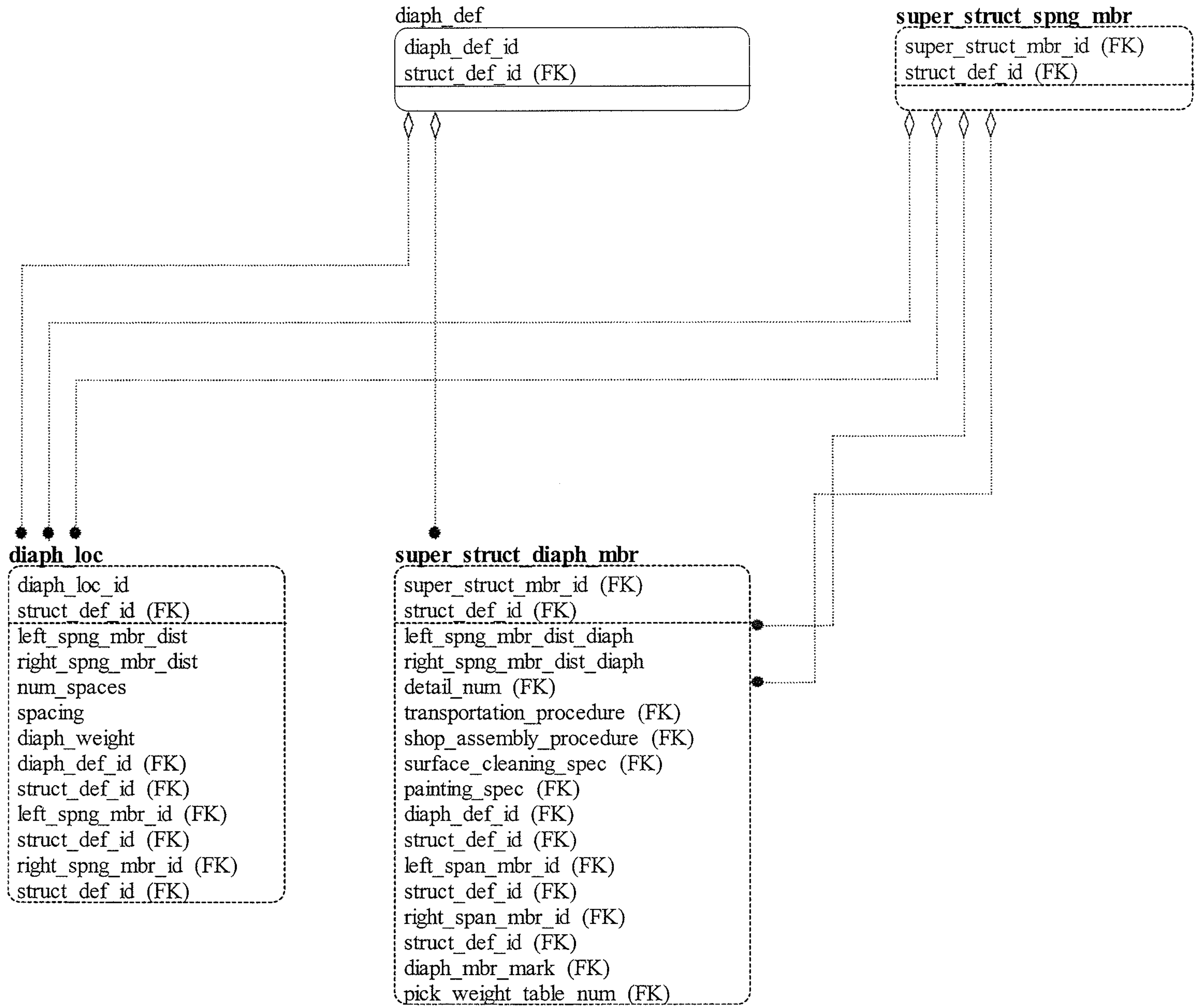
Pre-stressed girder fabrication and erection



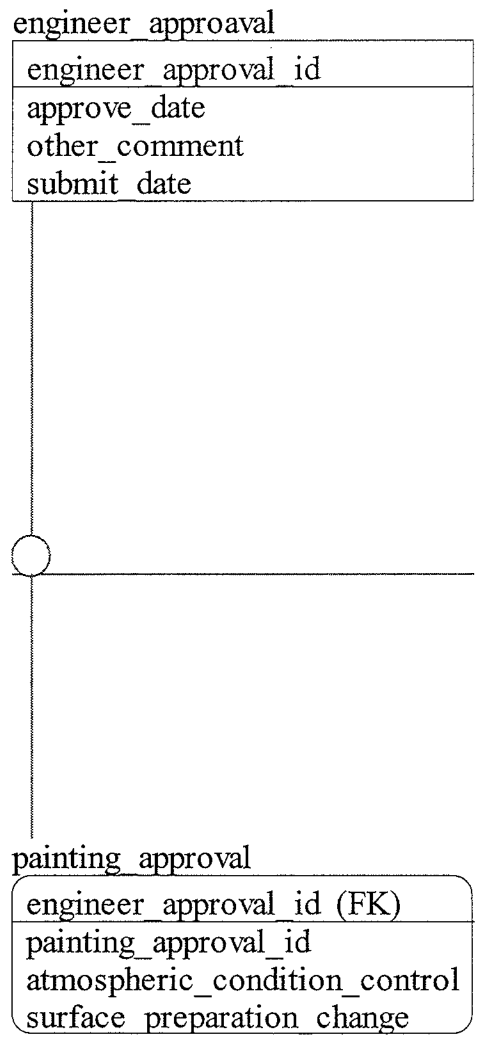
Bridge Bolt Field Type



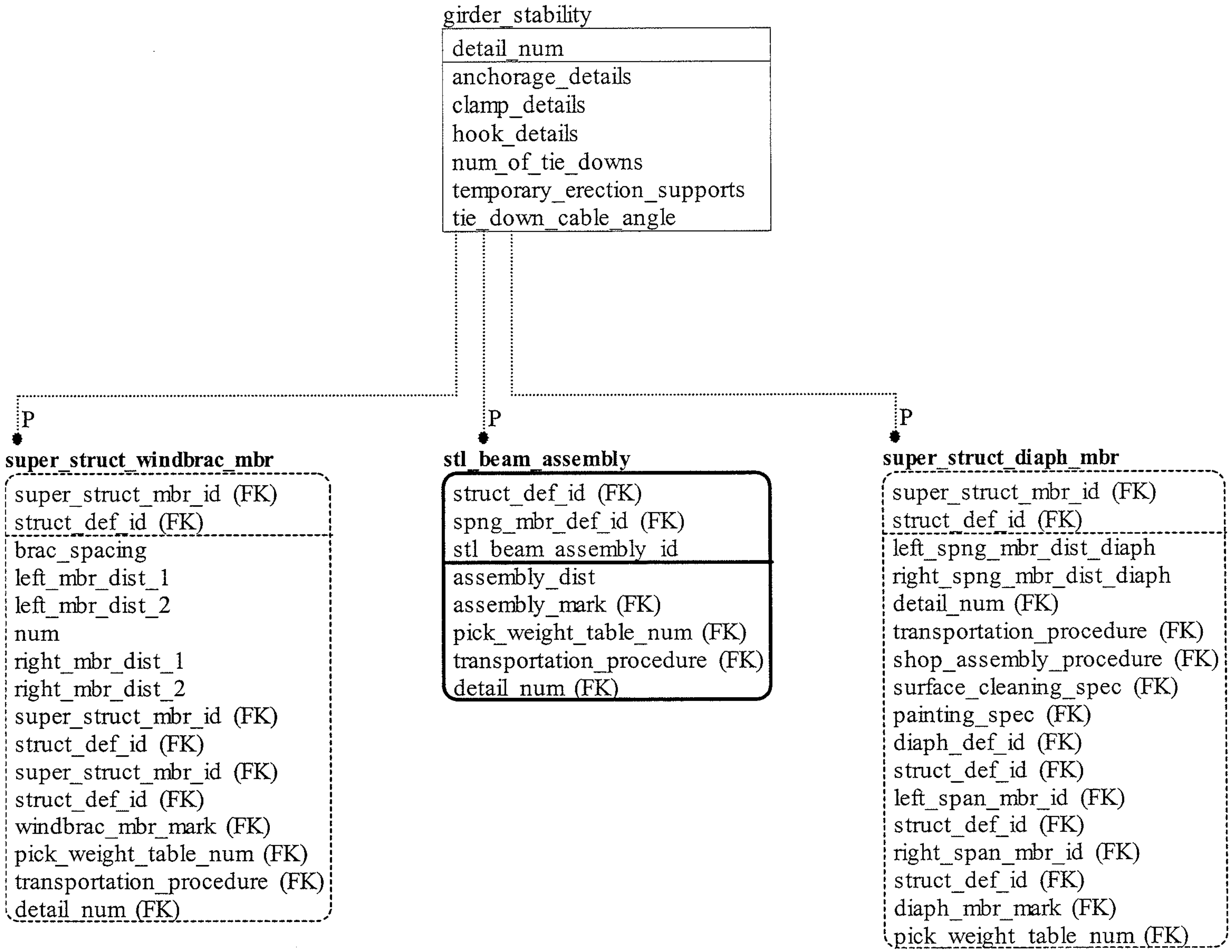
Crane Details


diaph_def
diaph_def_id
struct_def_id (FK)
super_struct_spng_mbr
super_struct_mbr_id (FK)
struct_def_id (FK)
diaph_loc
diaph_loc_id
struct_def_id (FK)
left_spng_mbr_dist
right_spng_mbr_dist
num_spaces
spacing
diaph_weight
diaph_def_id (FK)
struct_def_id (FK)
left_spng_mbr_id (FK)
struct_def_id (FK)
right_spng_mbr_id (FK)
struct_def_id (FK)
super_struct_diaph_mbr
super_struct_mbr_id (FK)
struct_def_id (FK)
left_spng_mbr_dist_diaph
right_spng_mbr_dist_diaph
detail_num (FK)
transportation_procedure (FK)
shop_assembly_procedure (FK)
surface_cleaning_spec (FK)
painting_spec (FK)
diaph_def_id (FK)
struct_def_id (FK)
left_span_mbr_id (FK)
struct_def_id (FK)
right_span_mbr_id (FK)
struct_def_id (FK)
diaph_mbr_mark (FK)
pick_weight_table_num (FK)

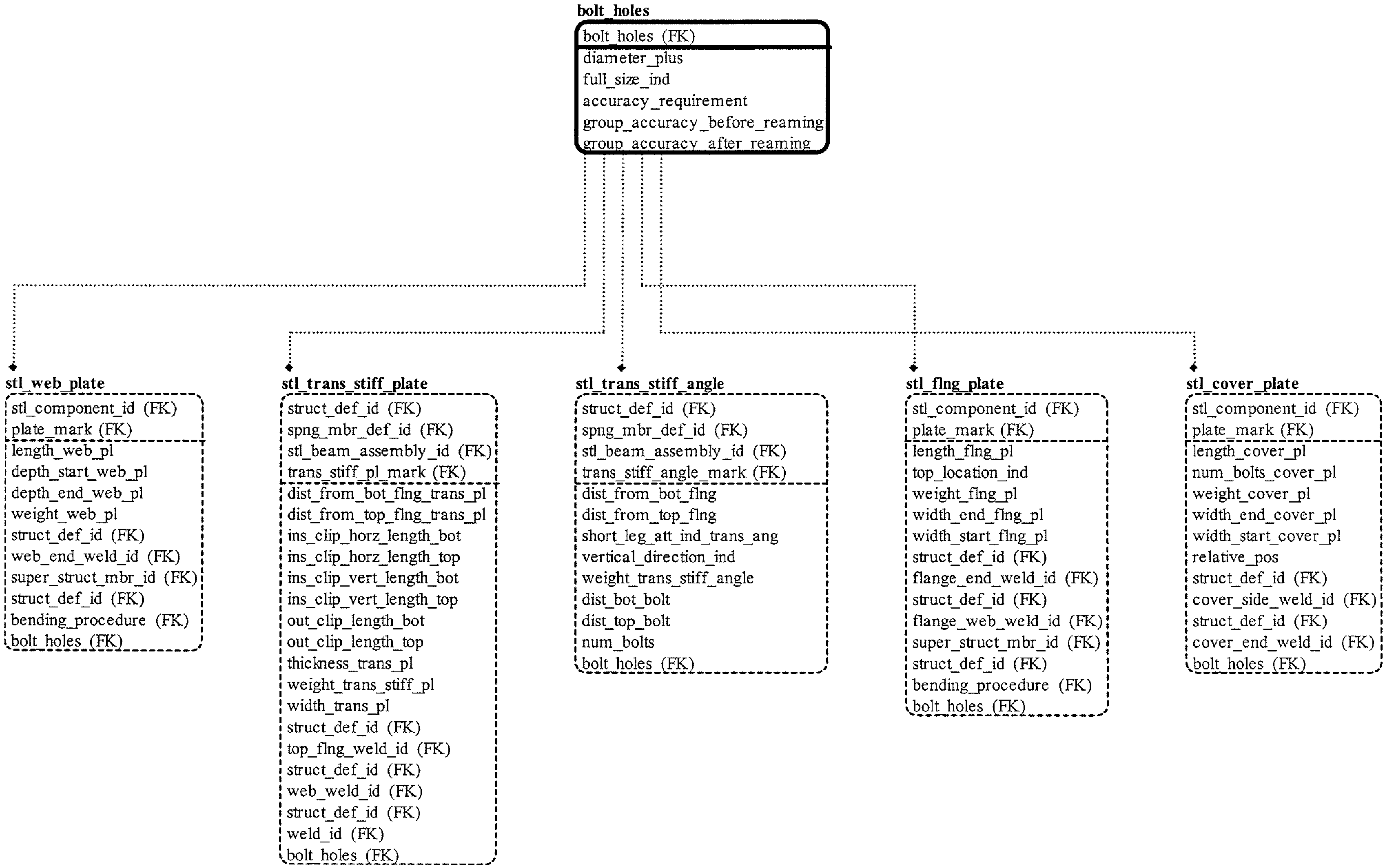
Diaphragm



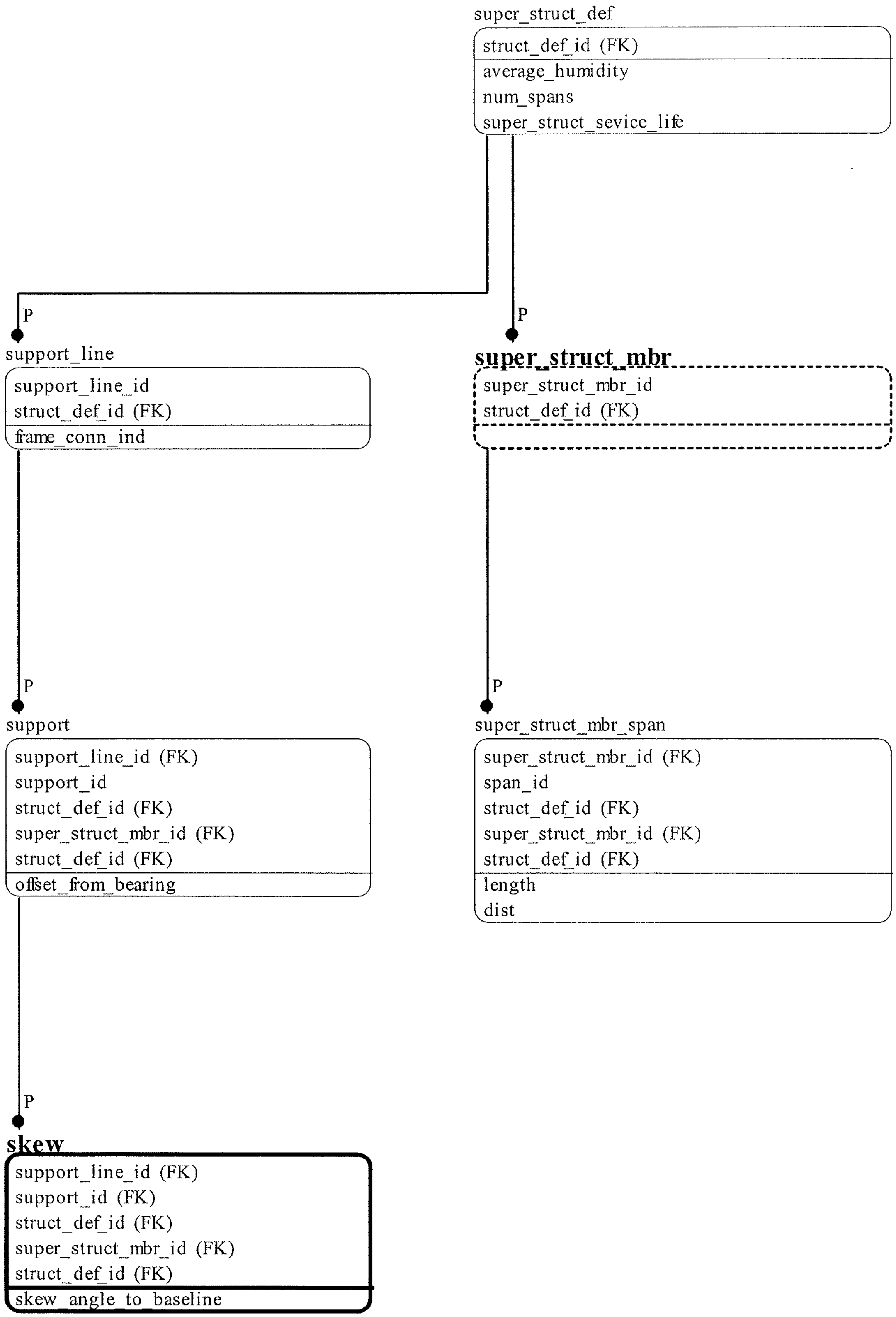
Engineering Approval (not fully complete)



Erection Stability



Fabricating Bolt Holes Procedure


super_struct_def
struct_def_id (FK)
average_humidity
num_spans
super_struct_sevice_life
P
P
support_line
support_line_id
struct_def_id (FK)
frame_conn_ind
super_struct_mbr
super_struct_mbr_id
struct_def_id (FK)
P
P
support
support_line_id (FK)
support_id
struct_def_id (FK)
super_struct_mbr_id (FK)
struct_def_id (FK)
offset_from_bearing
super_struct_mbr_span
super_struct_mbr_id (FK)
span_id
struct_def_id (FK)
super_struct_mbr_id (FK)
struct_def_id (FK)
length
dist
P
skew
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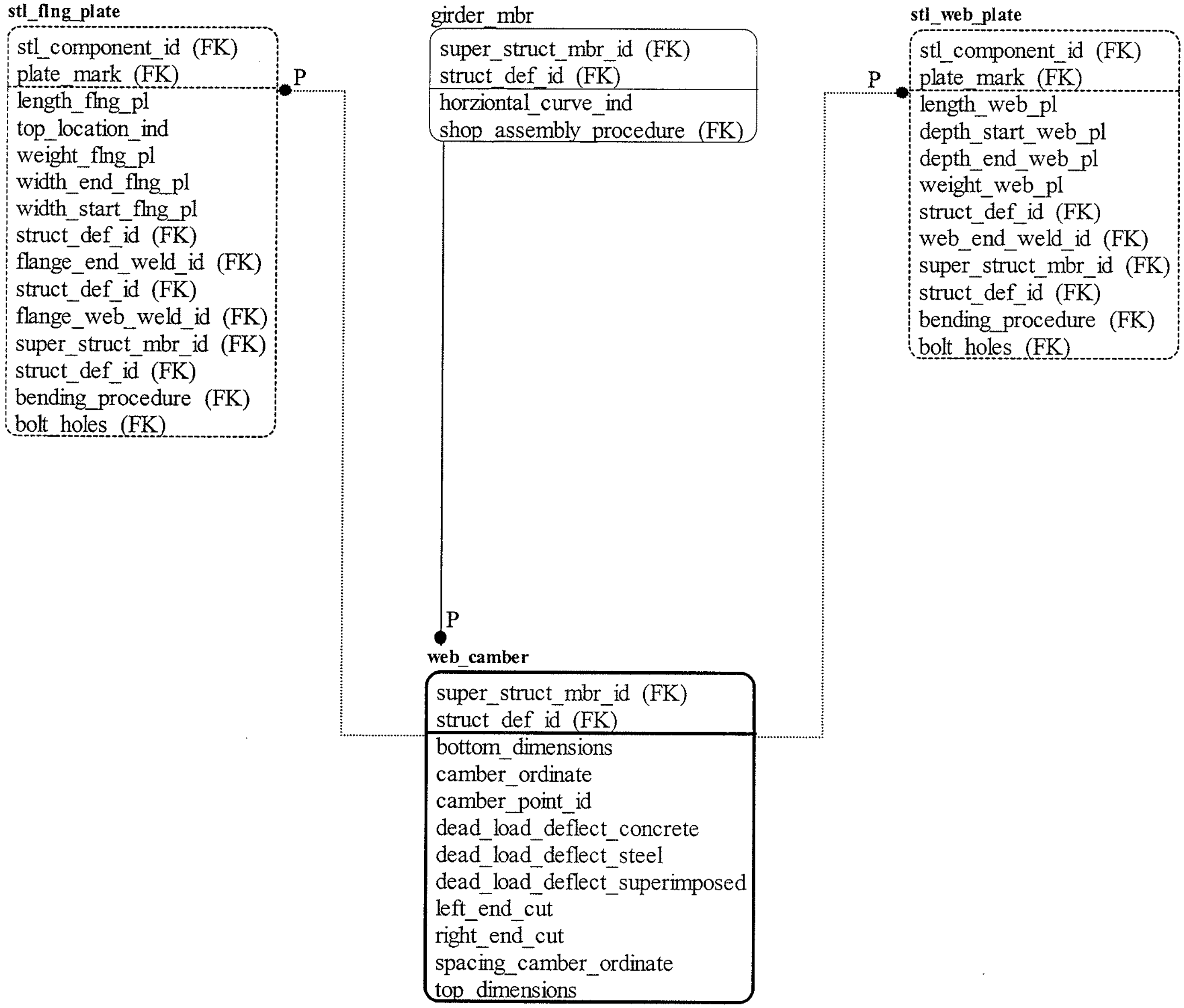
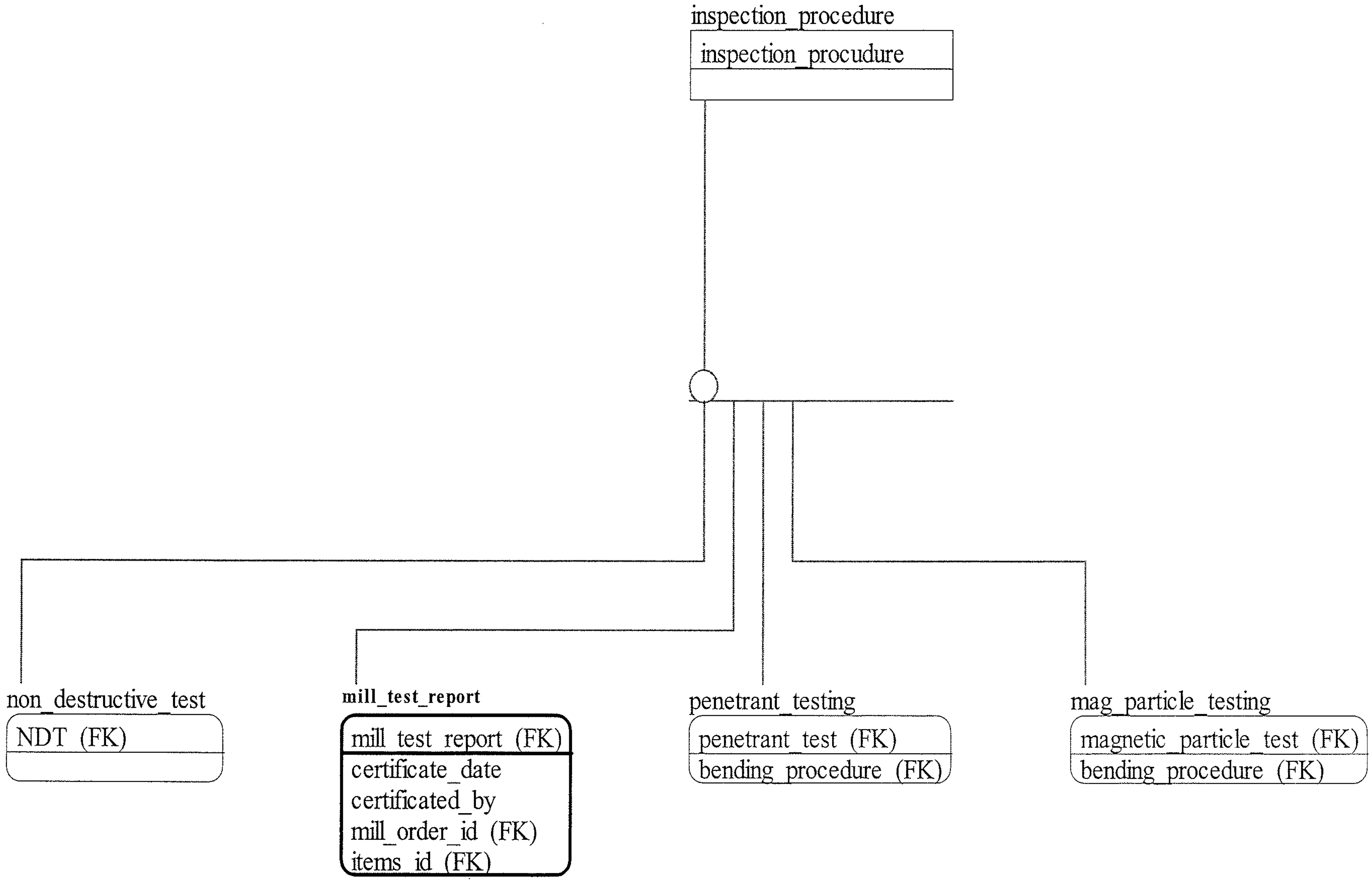
struct_def_id (FK)
super_struct_mbr_id (FK)
struct_def_id (FK)
skew_angle_to_baseline

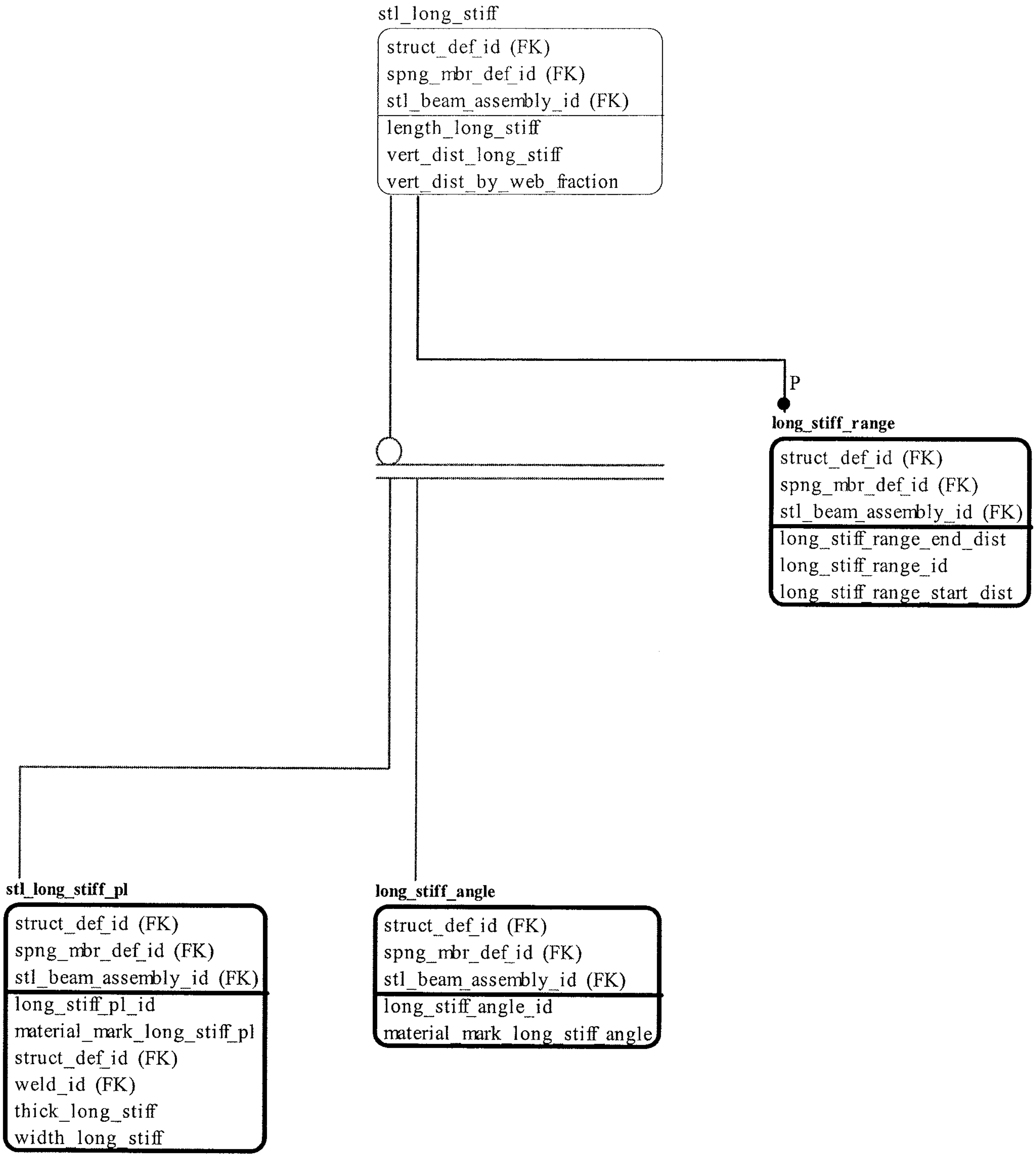
Framing



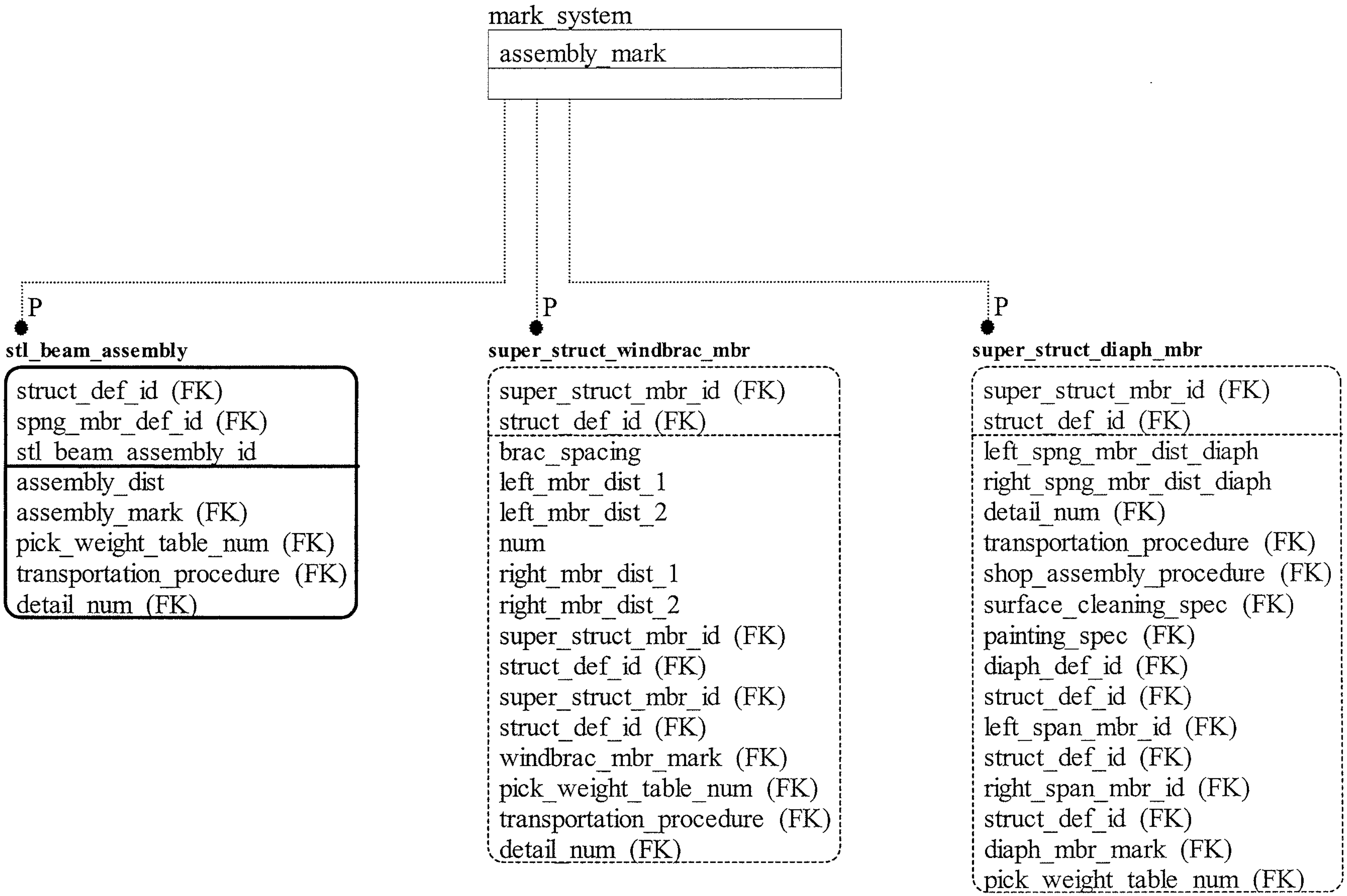
Girder Camber Detail



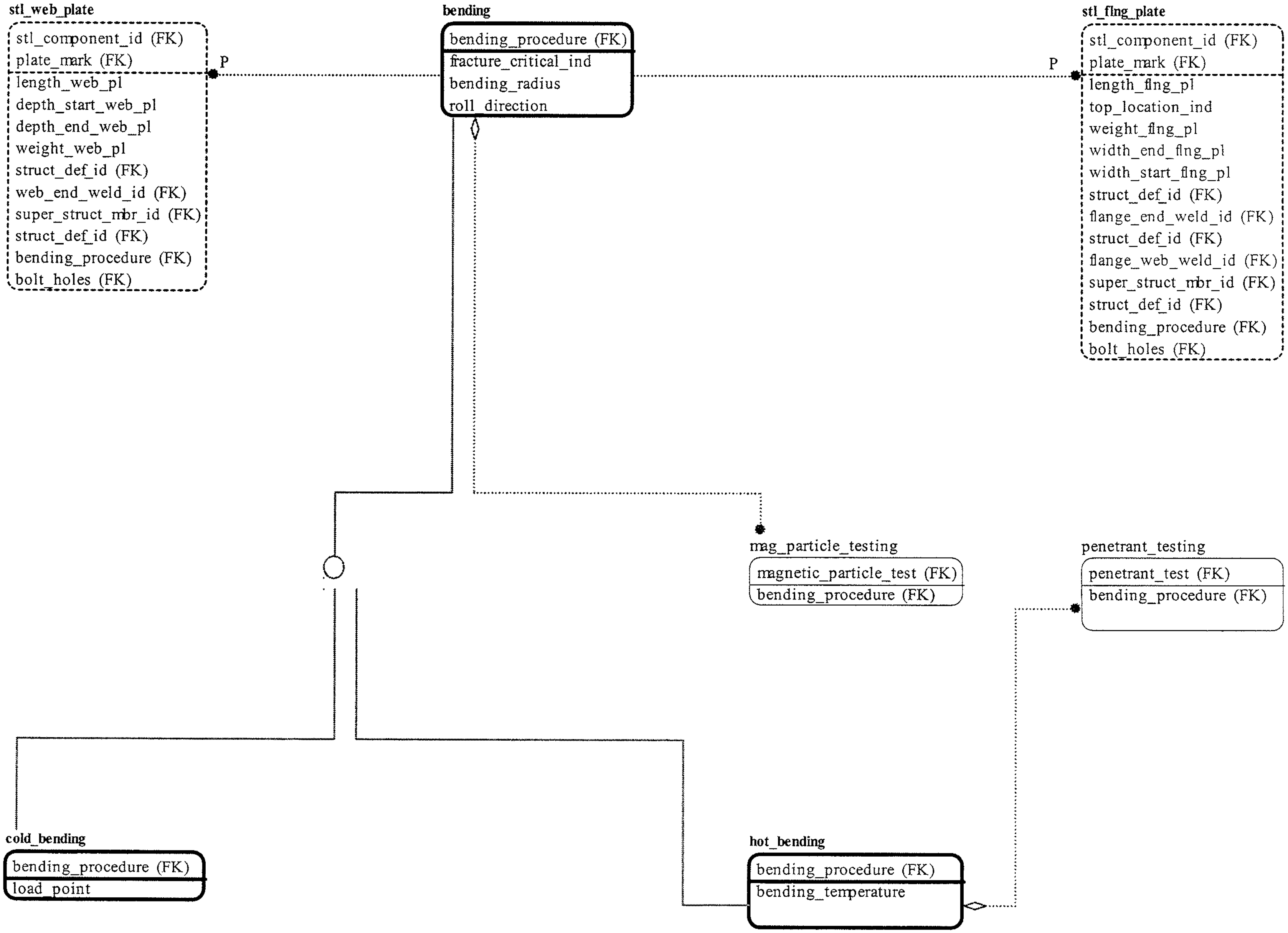
Inspection Procedure (not fully complete)



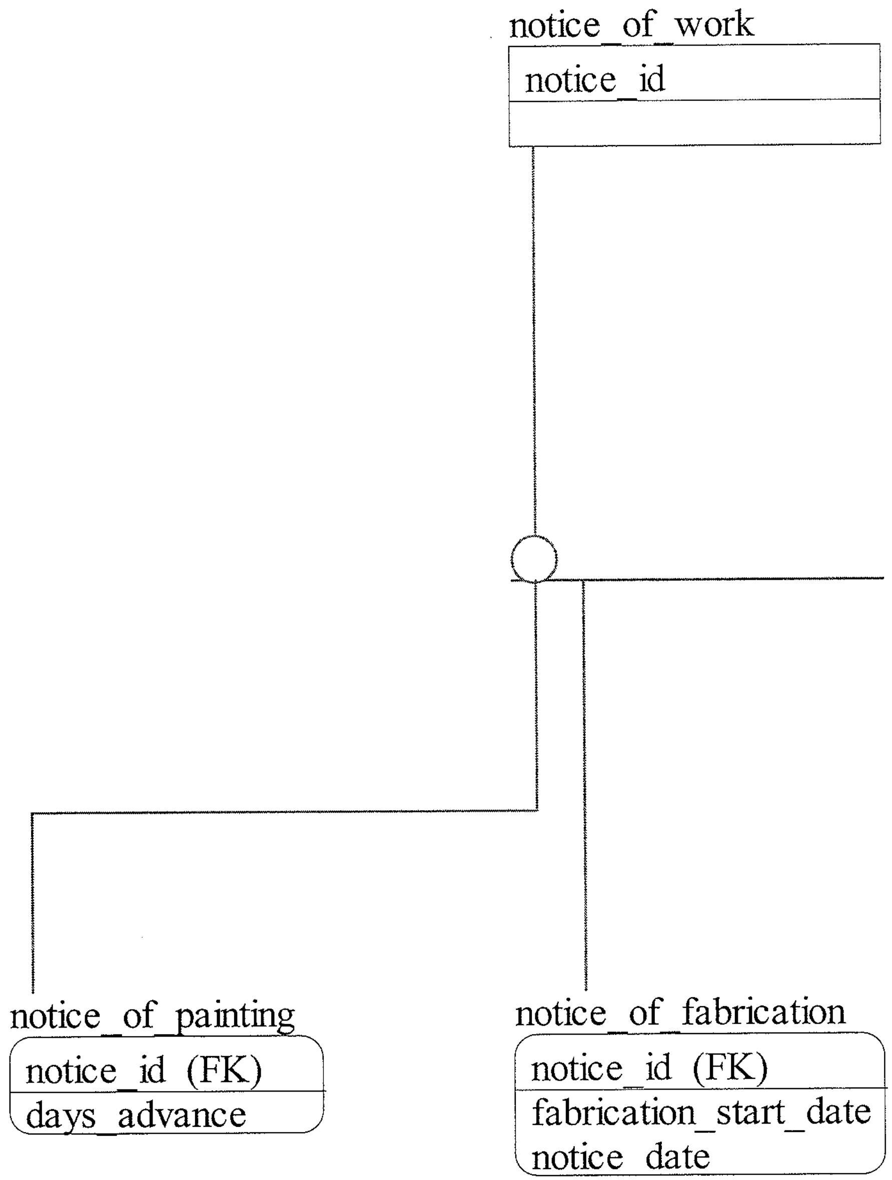
Longitudinal Stiffener



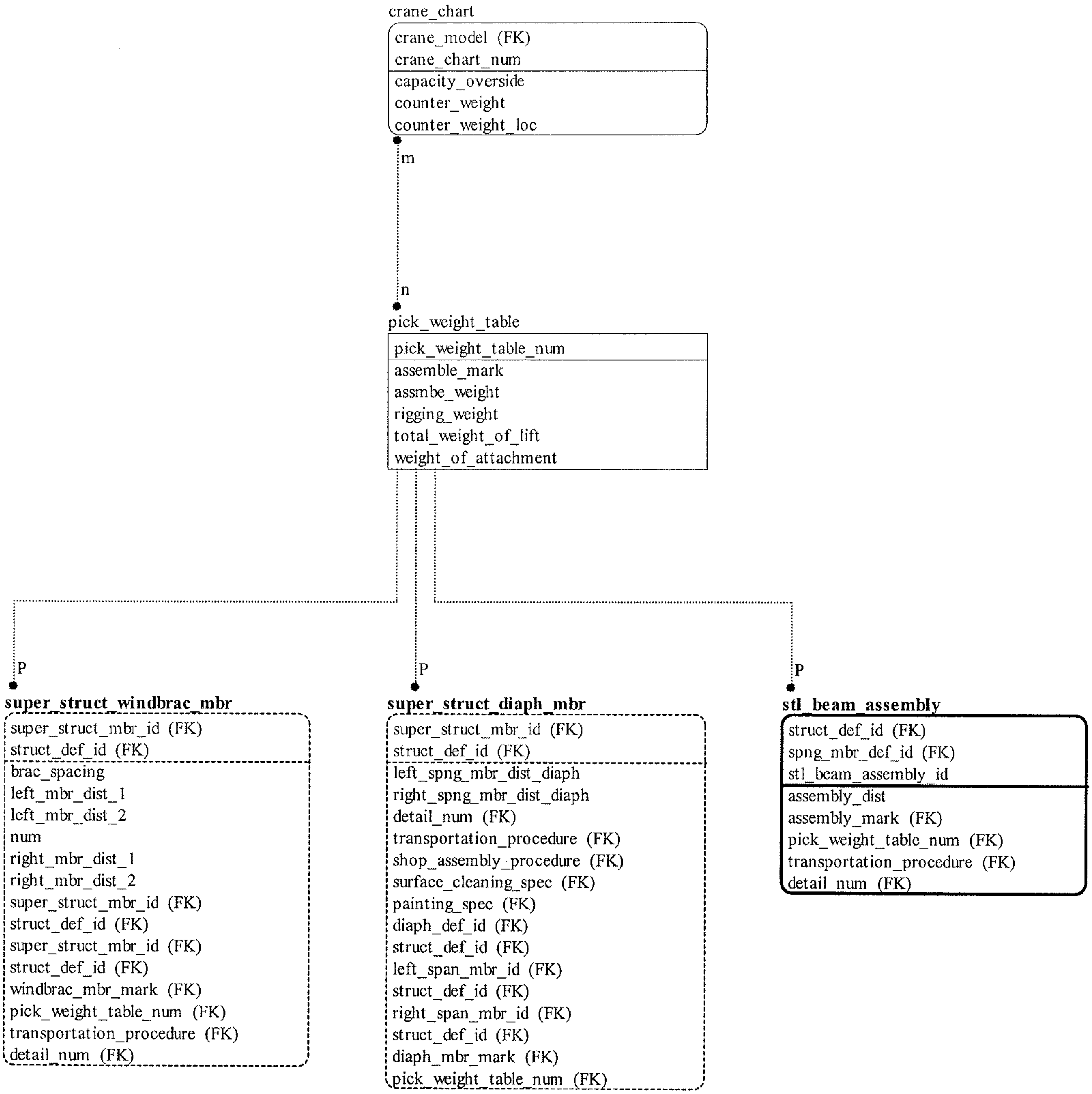
Mark System (Assembly Part)



Member Bending Procedure



Notice Type (not fully complete)


crane_chart
crane_model (FK)
crane_chart_num
capacity_overside
counter_weight
counter_weight_loc
m
n
pick_weight_table
pick_weight_table_num
assemble_mark
assmbe_weight
rigging_weight
total_weight_of_lift
weight_of_attachment
P
P
P
super_struct_windbrac_mbr
super_struct_mbr_id (FK)
struct_def_id (FK)
brac_spacing
left_mbr_dist_1
left_mbr_dist_2
num
right_mbr_dist_1
right_mbr_dist_2
super_struct_mbr_id (FK)
struct_def_id (FK)
super_struct_mbr_id (FK)
struct_def_id (FK)
windbrac_mbr_mark (FK)
pick_weight_table_num (FK)
transportation_procedure (FK)
detail_num (FK)
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left_spng_mbr_dist_diaph
right_spng_mbr_dist_diaph
detail_num (FK)
transportation_procedure (FK)
shop_assembly_procedure (FK)
surface_cleaning_spec (FK)
painting_spec (FK)
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struct_def_id (FK)
left_span_mbr_id (FK)
struct_def_id (FK)
right_span_mbr_id (FK)
struct_def_id (FK)
diaph_mbr_mark (FK)
pick_weight_table_num (FK)
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struct_def_id (FK)
spng_mbr_def_id (FK)
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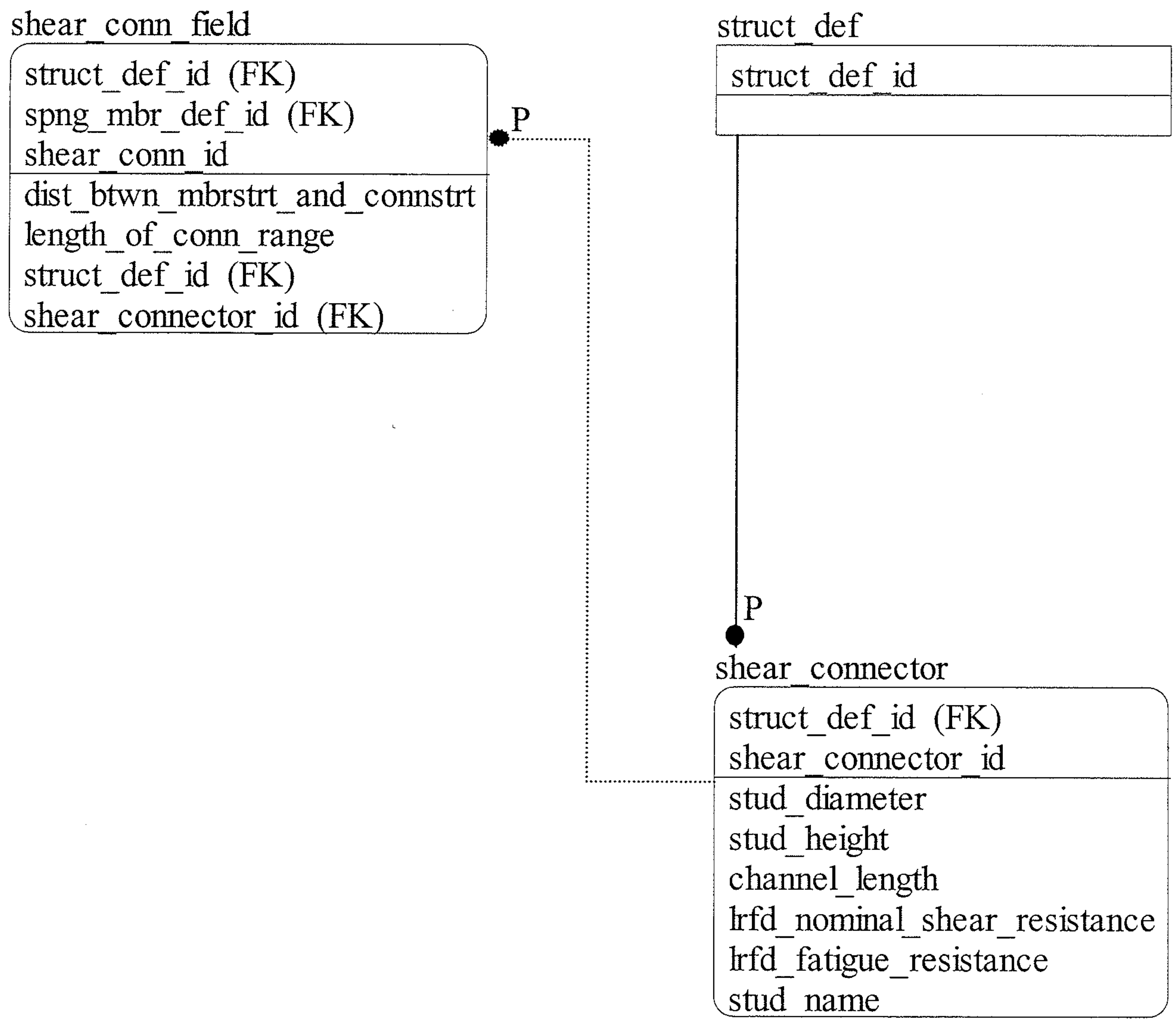
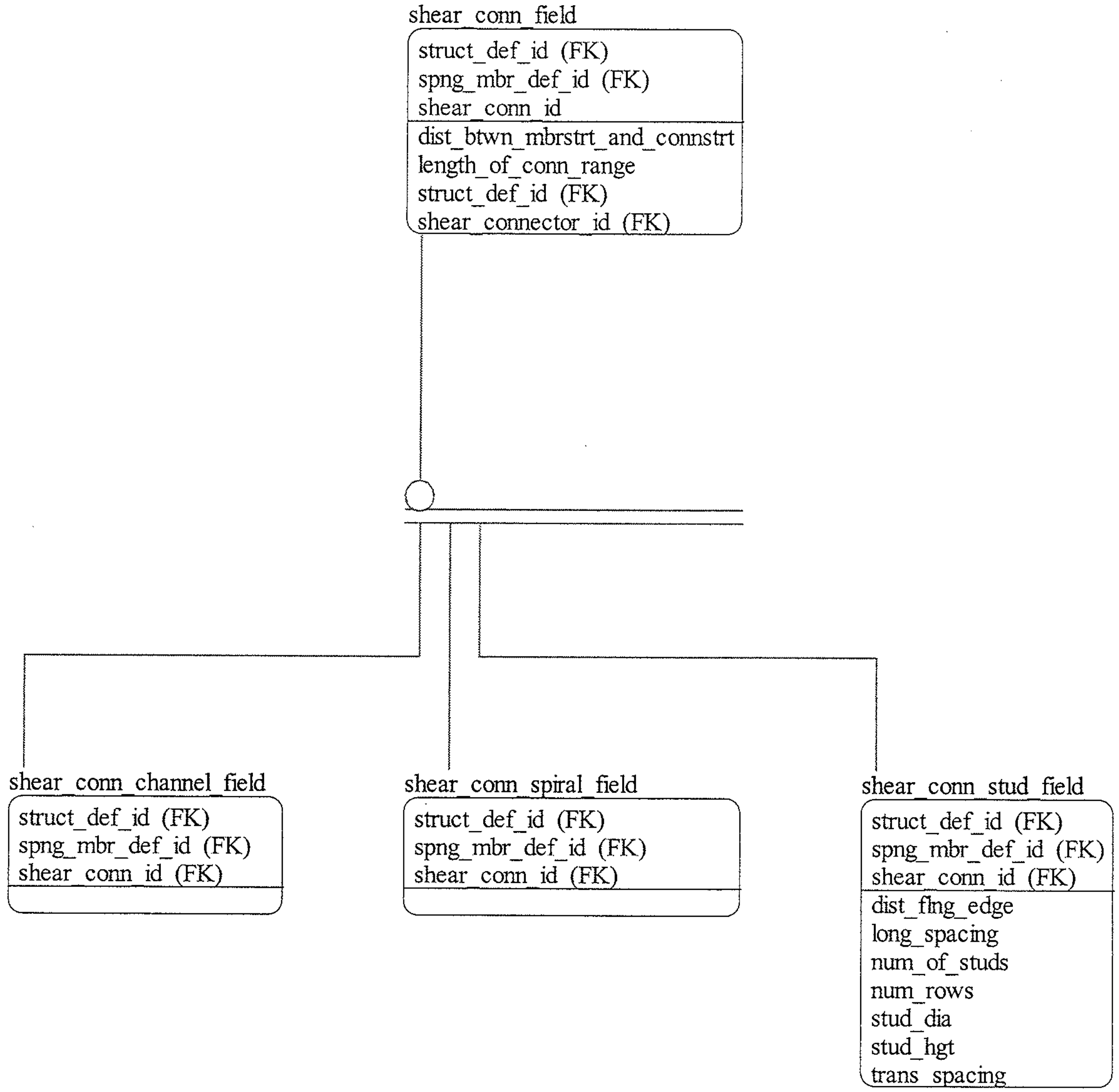
transportation_procedure (FK)
detail_num (FK)

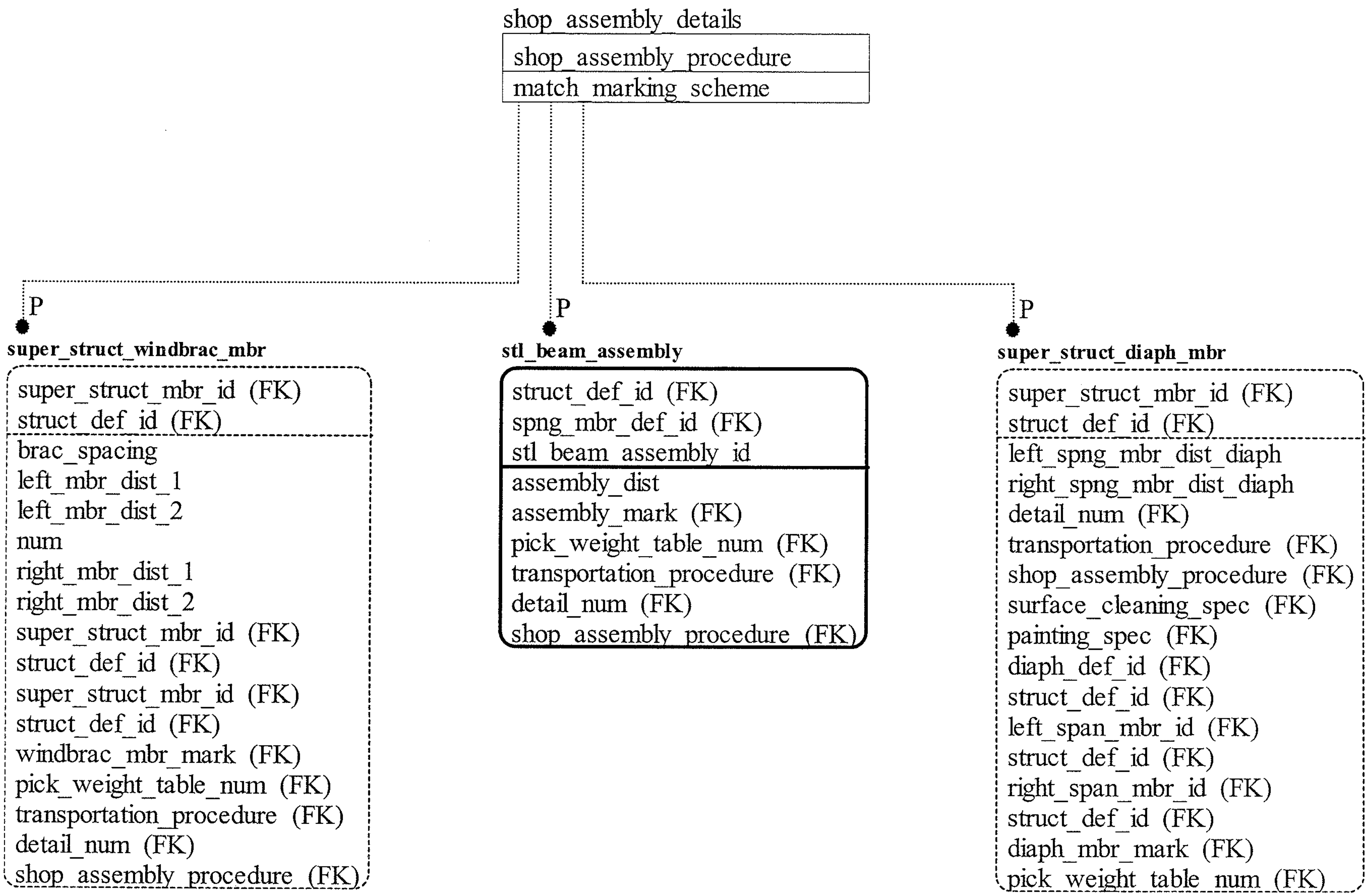
Pick Weight



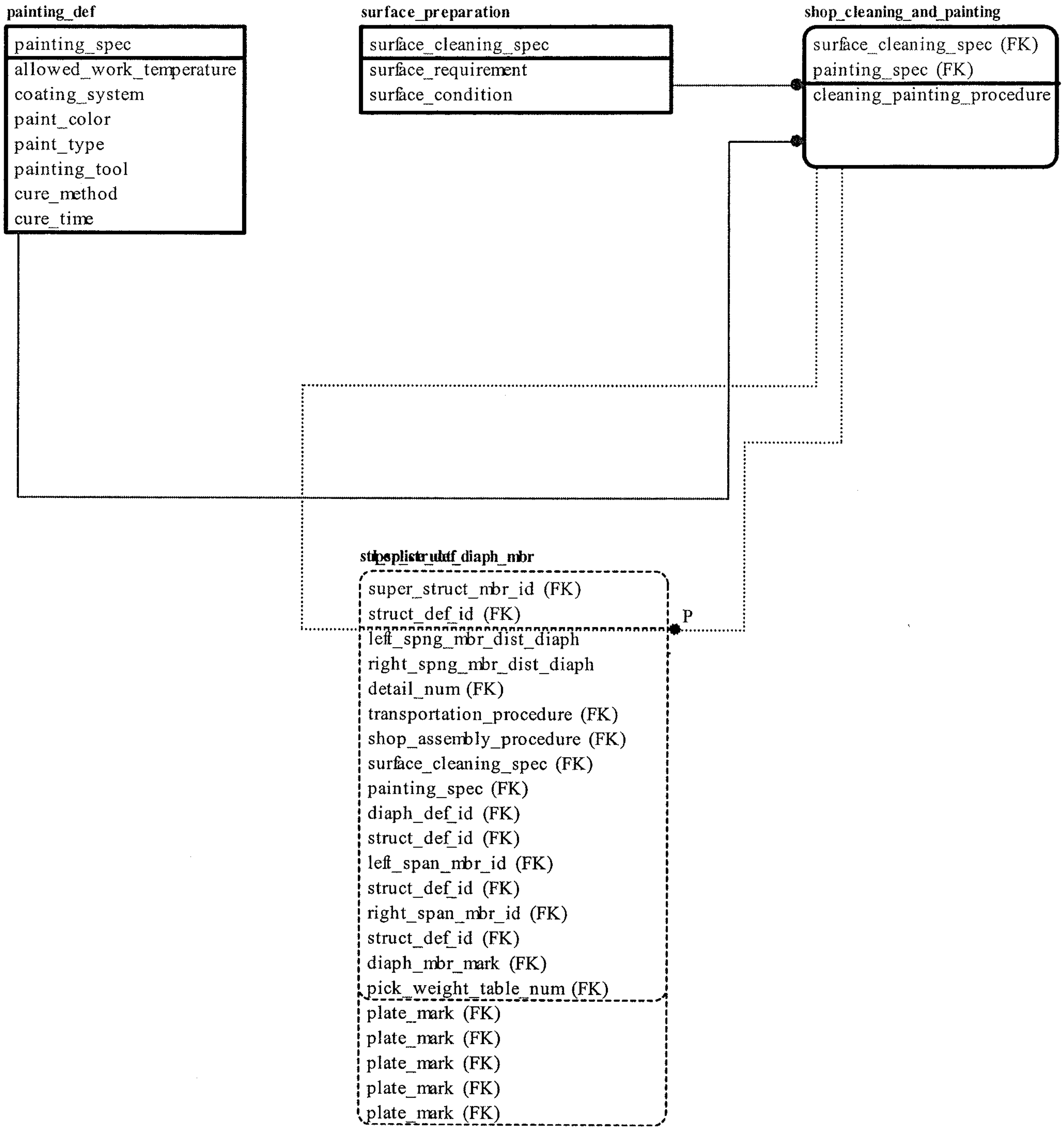
Shear Connector



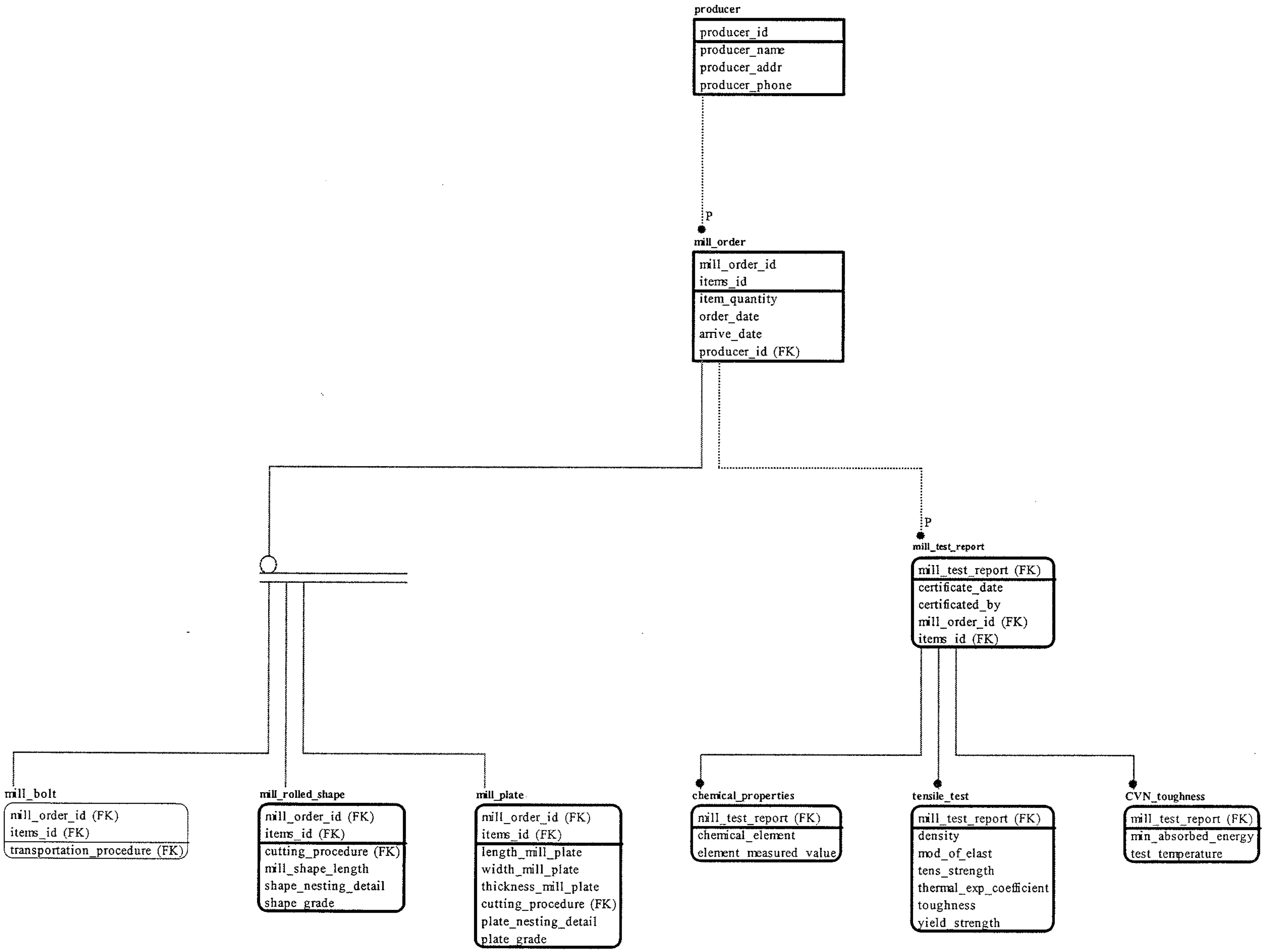
Shear Connector Field Type



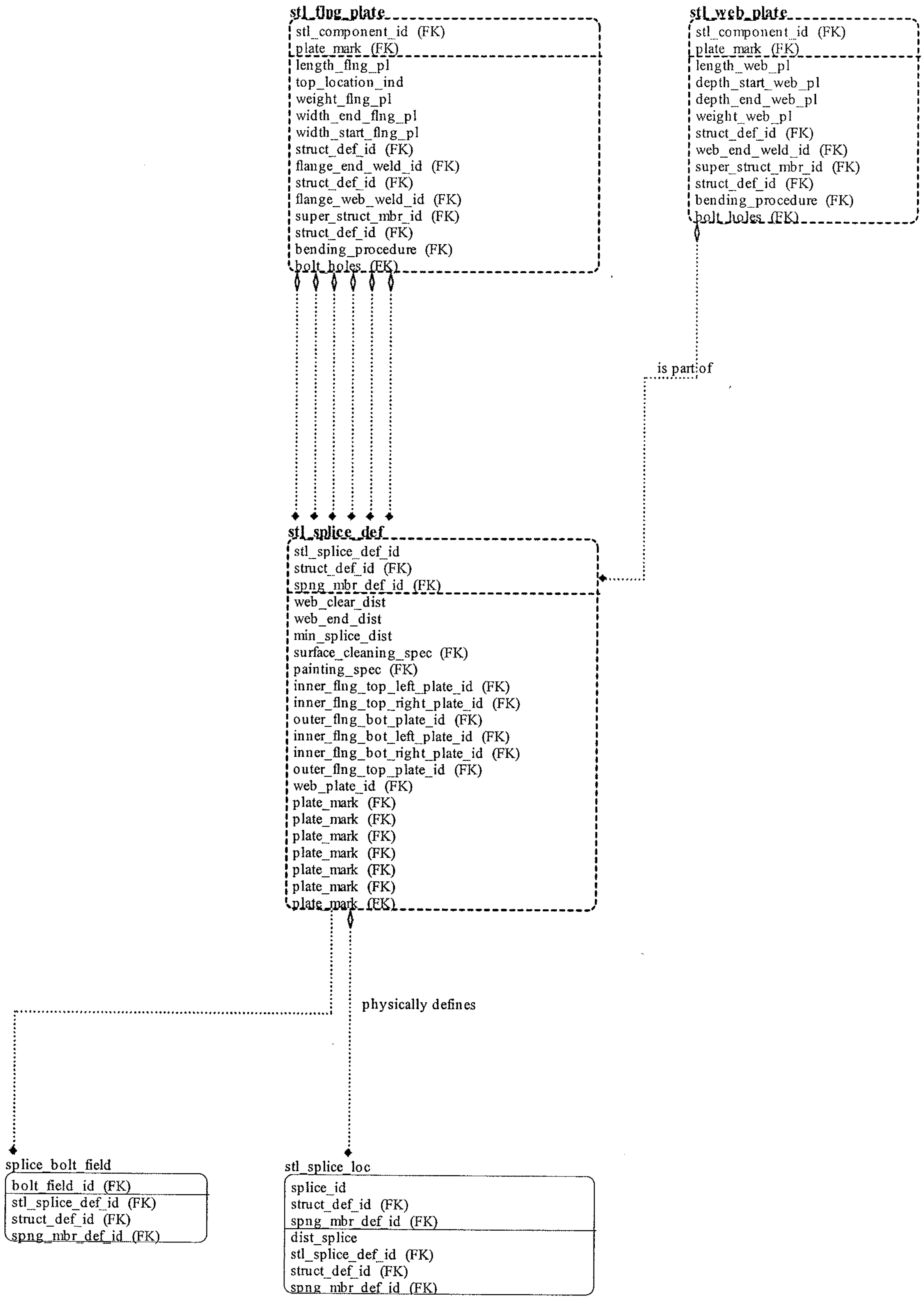
Shop Assembly Details



Shop Cleaning and Painting



Shop Material Detail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plate_mark (FK)
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top_location_ind
weight_flng_pl
width_end_flng_pl
width_start_flng_pl
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flange_end_weld_id (FK)
struct_def_id (FK)
flange_web_weld_id (FK)
super_struct_mbr_id (FK)
struct_def_id (FK)
bending_procedure (FK)
bolt_holes (FK)
stl_web_plate
stl_component_id (FK)
plate_mark (FK)
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depth_end_web_pl
weight_web_pl
struct_def_id (FK)
web_end_weld_id (FK)
super_struct_mbr_id (FK)
struct_def_id (FK)
bending_procedure (FK)
bolt_holes (FK)
is part of
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struct_def_id (FK)
spng_mbr_def_id (FK)
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web_end_dist
min_splice_dist
surface_cleaning_spec (FK)
painting_spec (FK)
inner_flng_top_left_plate_id (FK)
inner_flng_top_right_plate_id (FK)
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web_plate_id (FK)
plate_mark (FK)
plate_mark (FK)
plate_mark (FK)
plate_mark (FK)
plate_mark (FK)
plate_mark (FK)
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bolt_field_id (FK)
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struct_def_id (FK)
spng_mbr_def_id (FK)
stl_splice_loc
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struct_def_id (FK)
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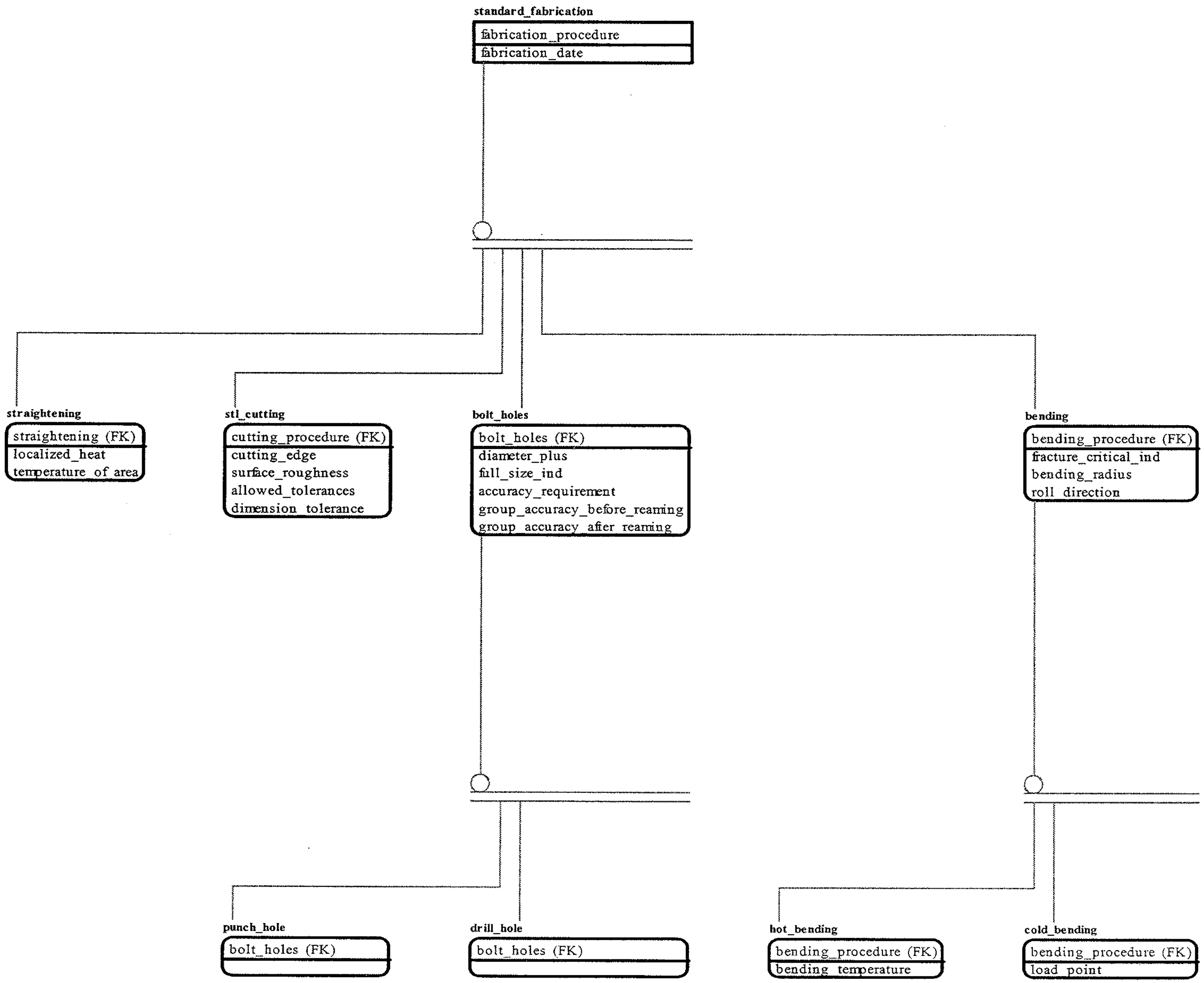
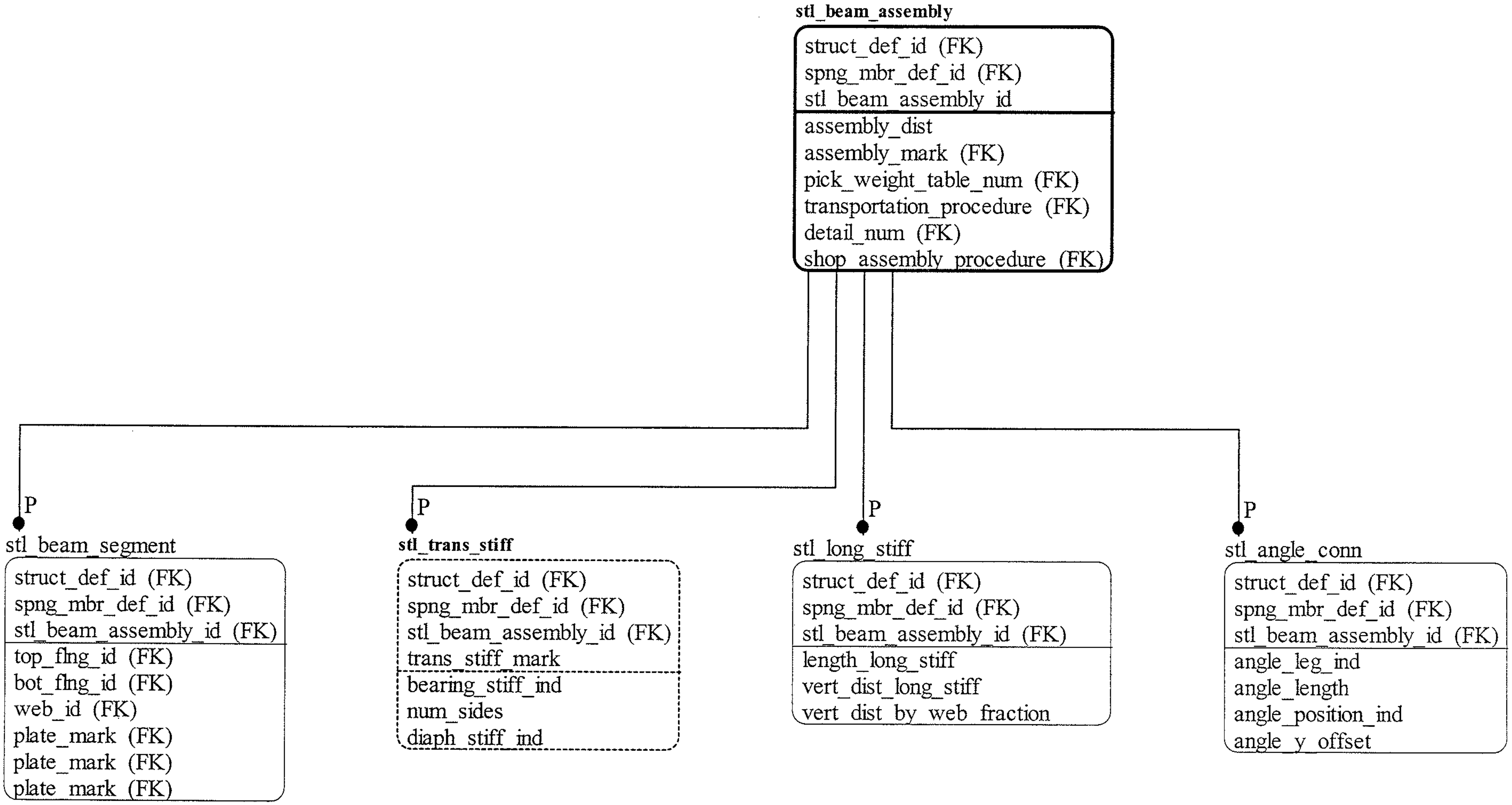
spng_mbr_def_id (FK)

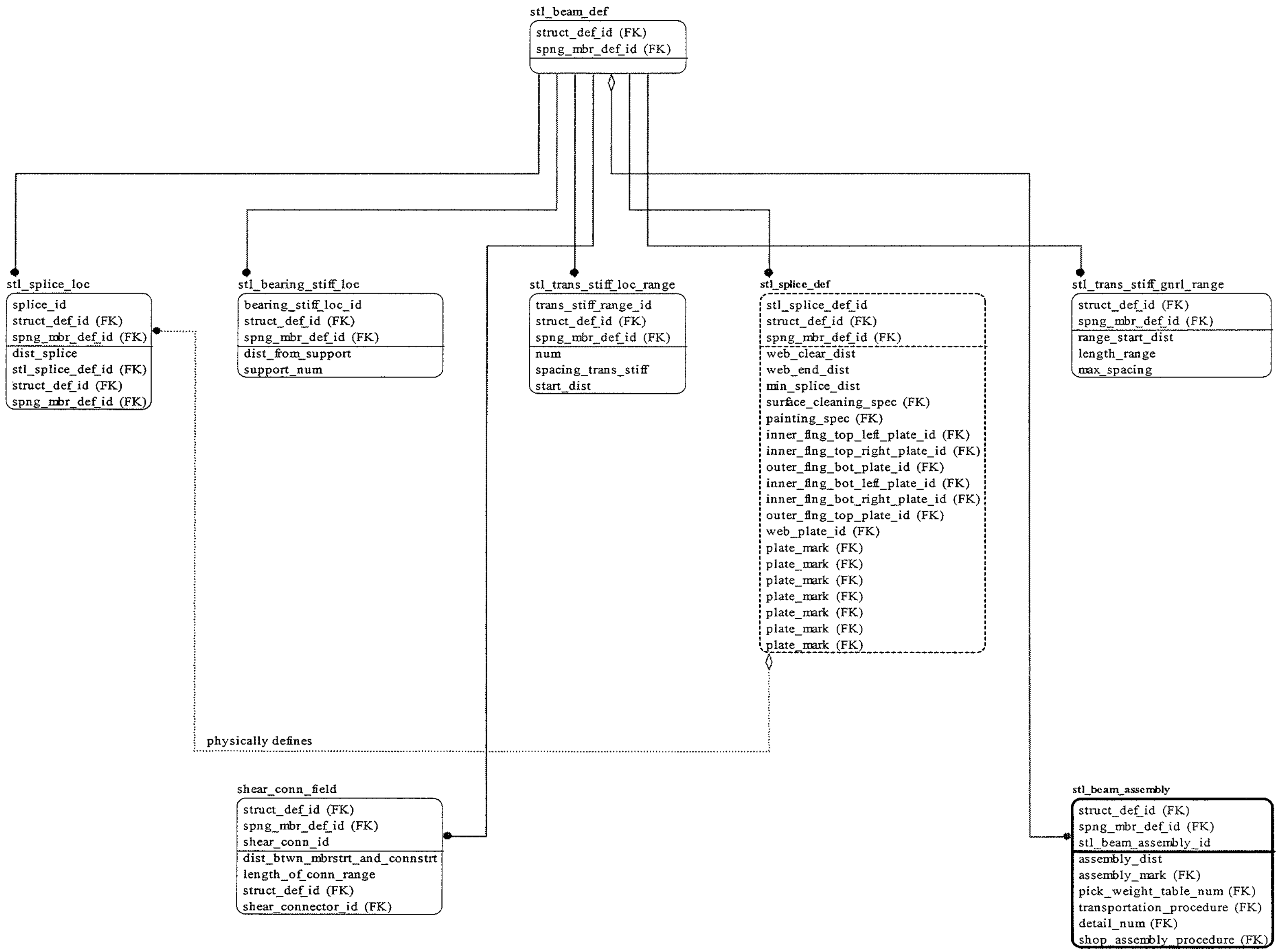
Splice



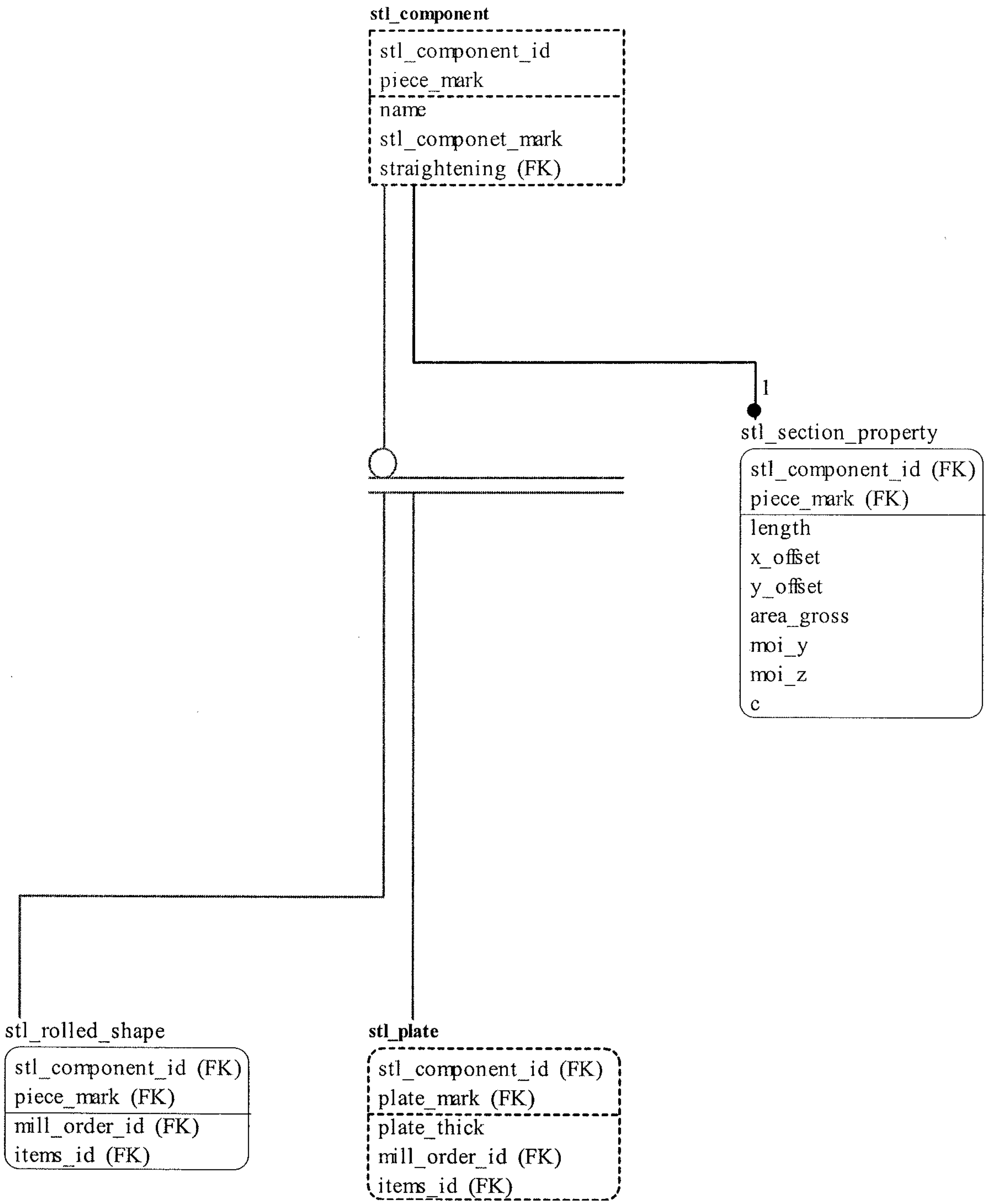
Standard Fabrication Process



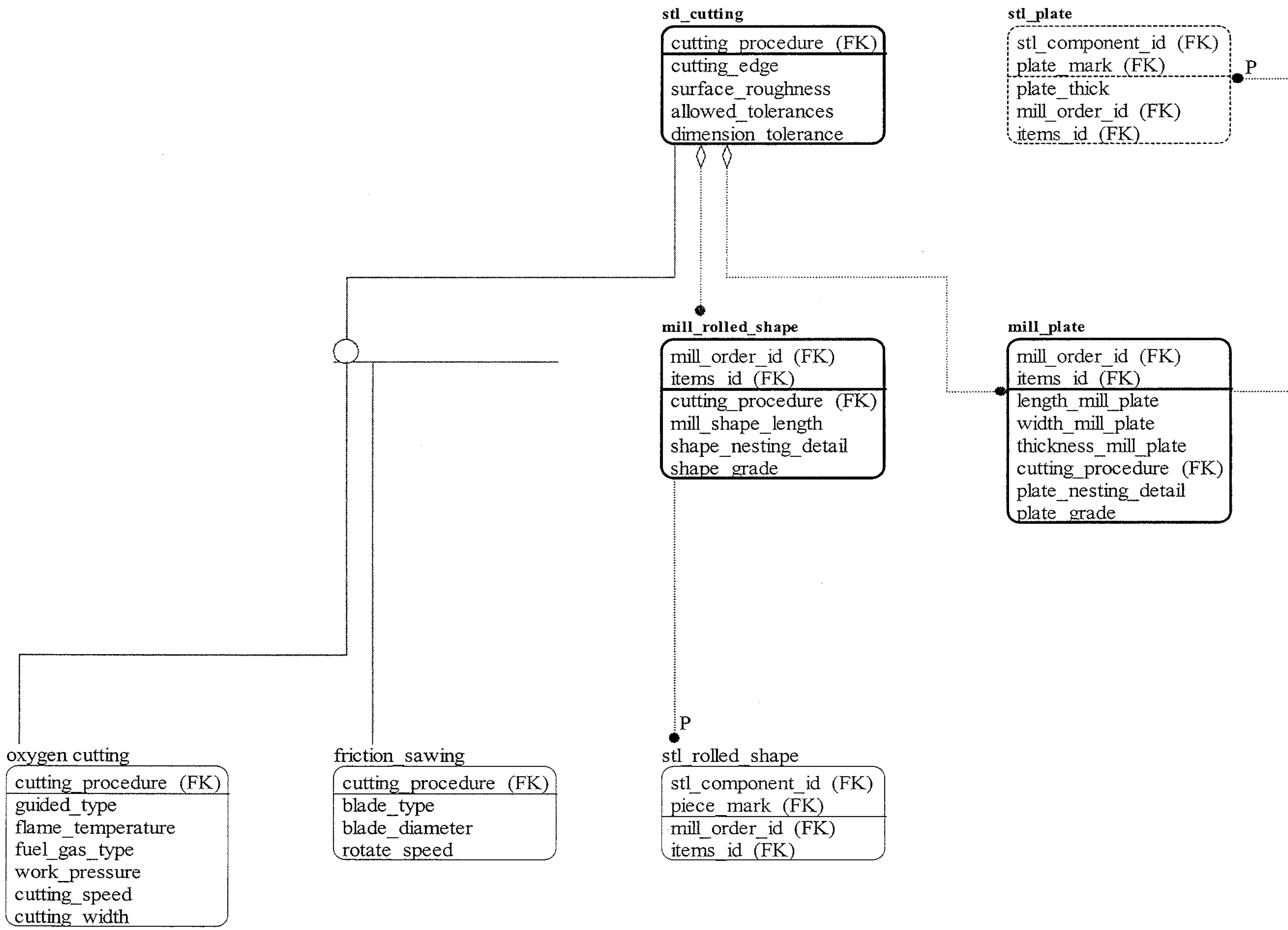
Steel Beam Assemble Detail



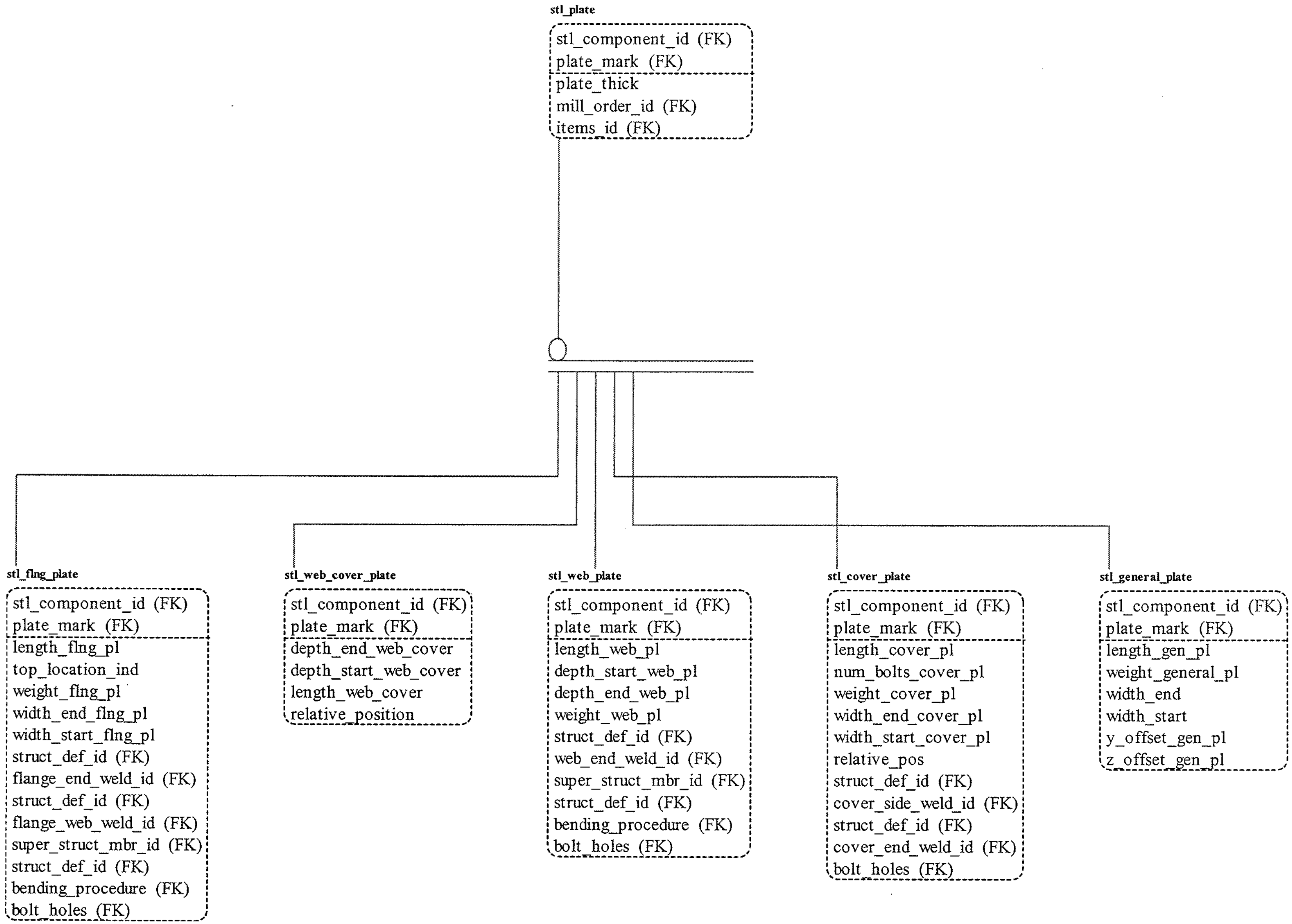
Steel Beam Definition



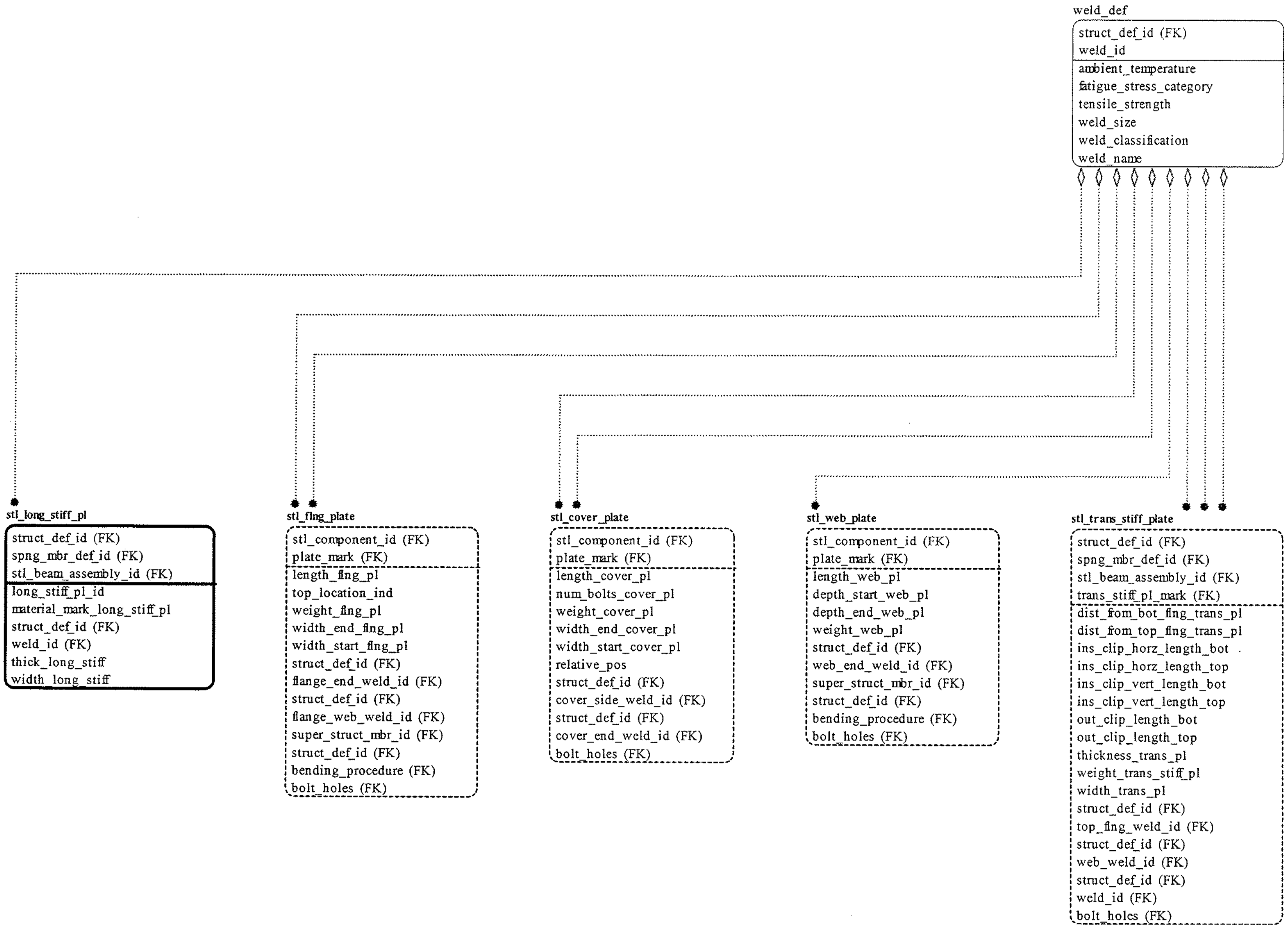
Steel Component Type



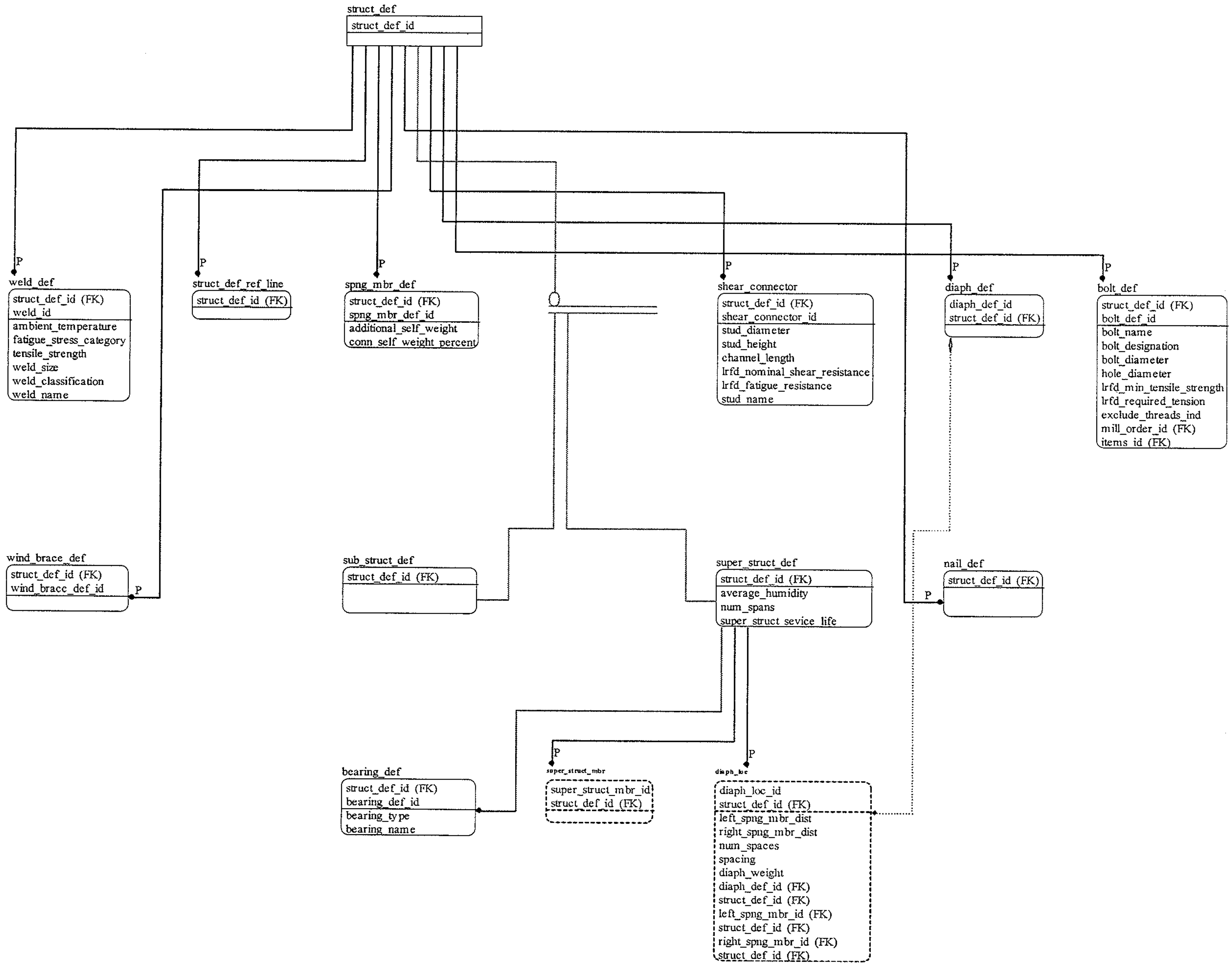
Steel Cutting Detail



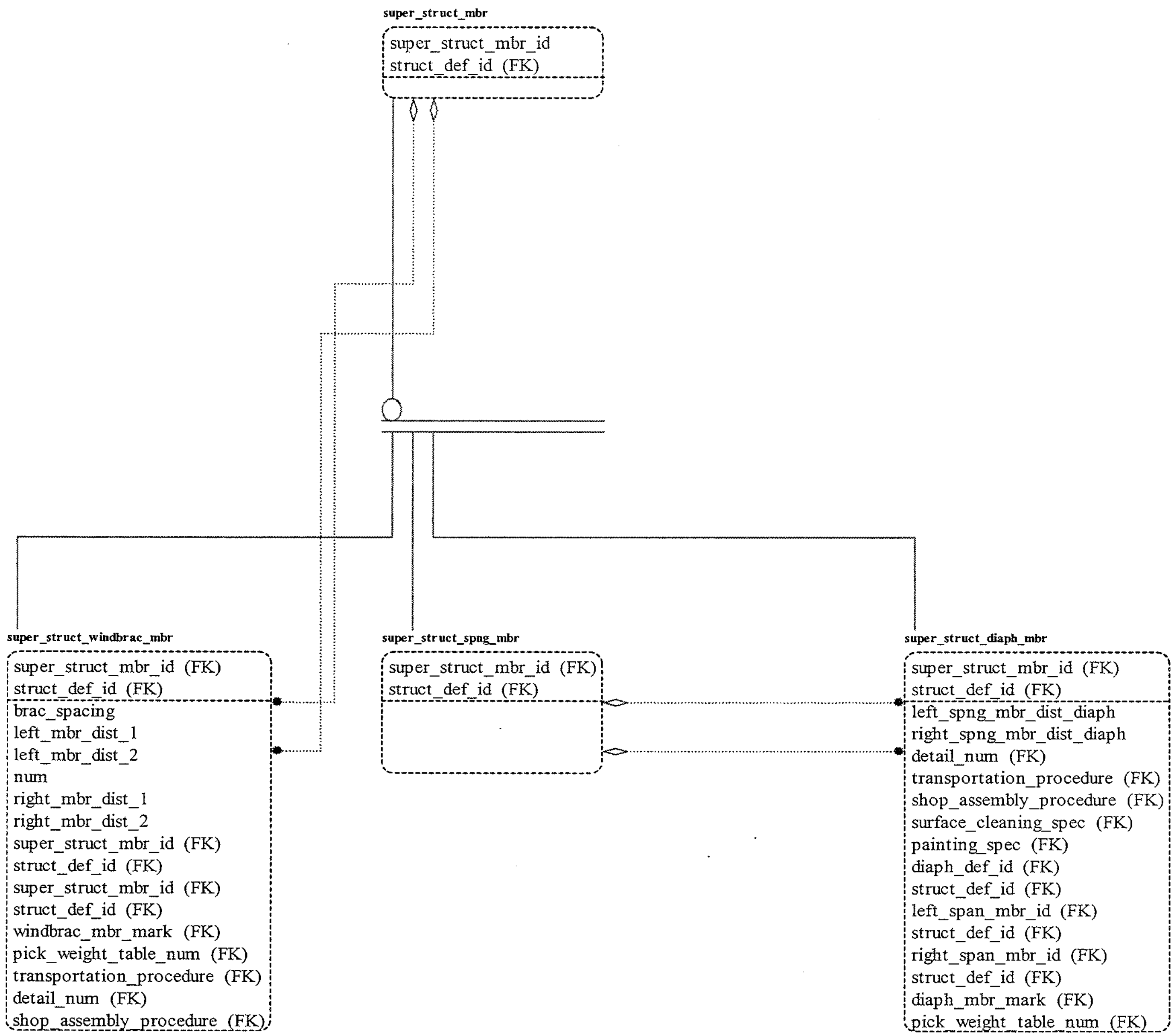
Steel Plate Type



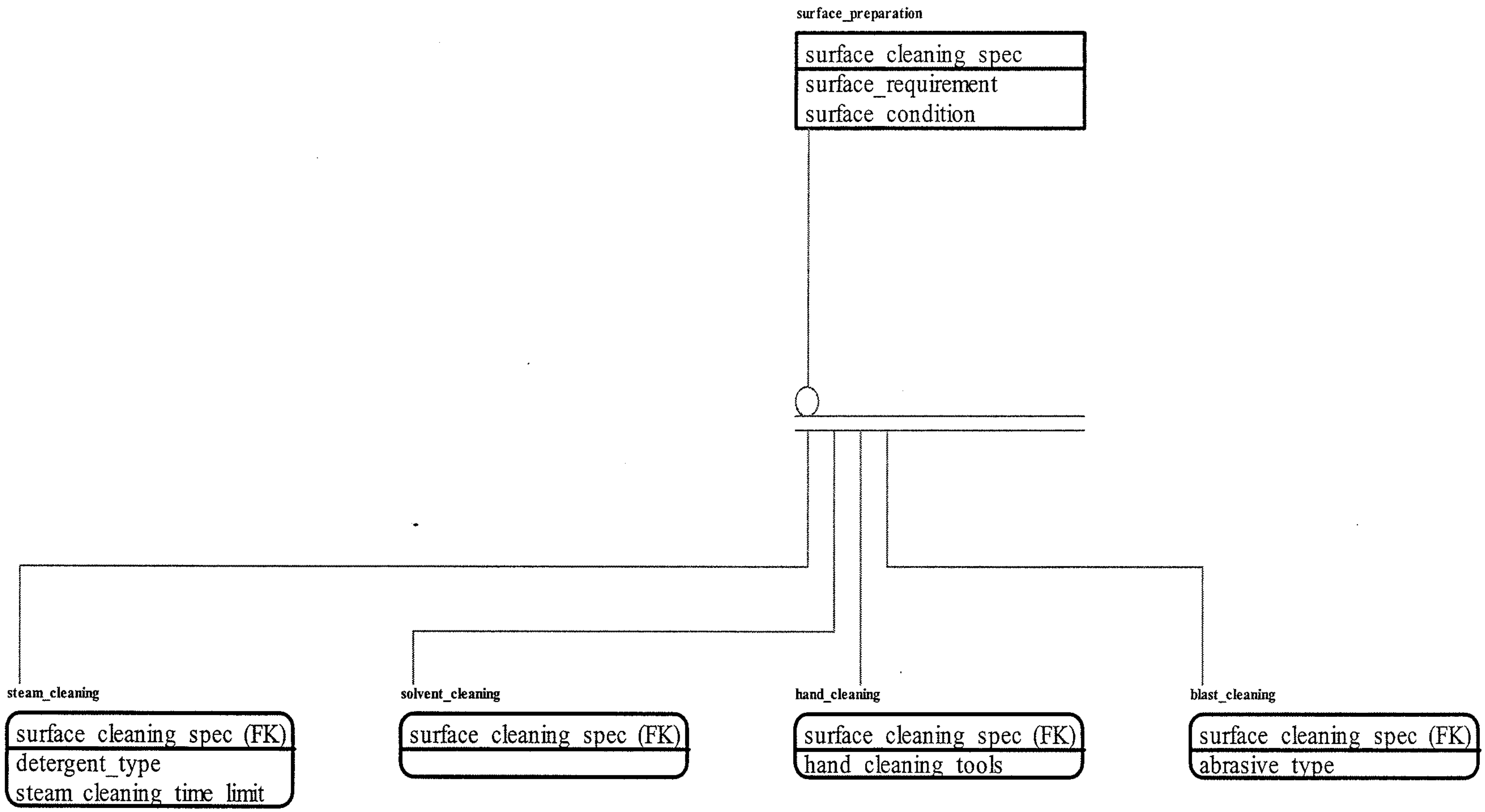
Steel Plate Welding



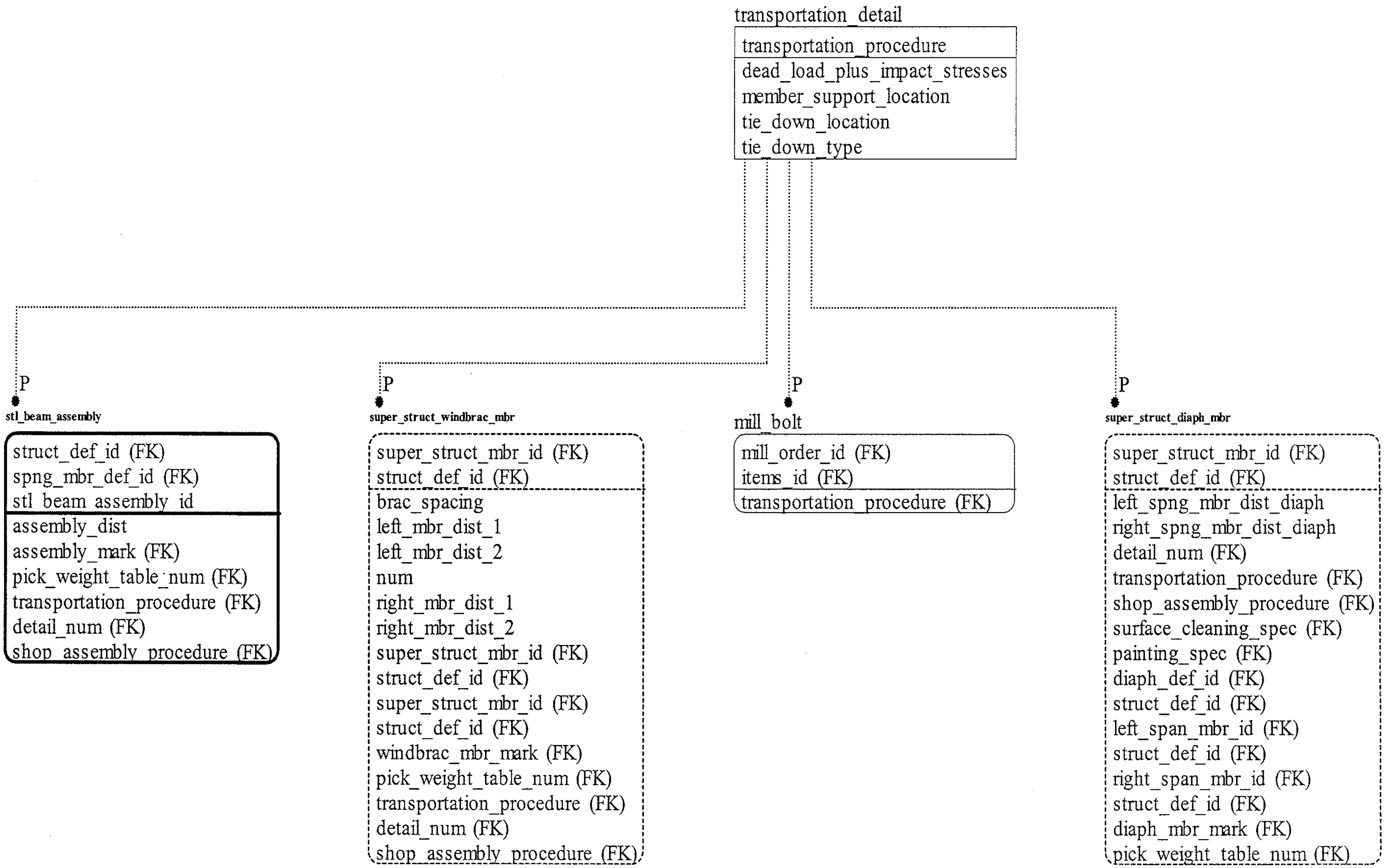
Structure Definition



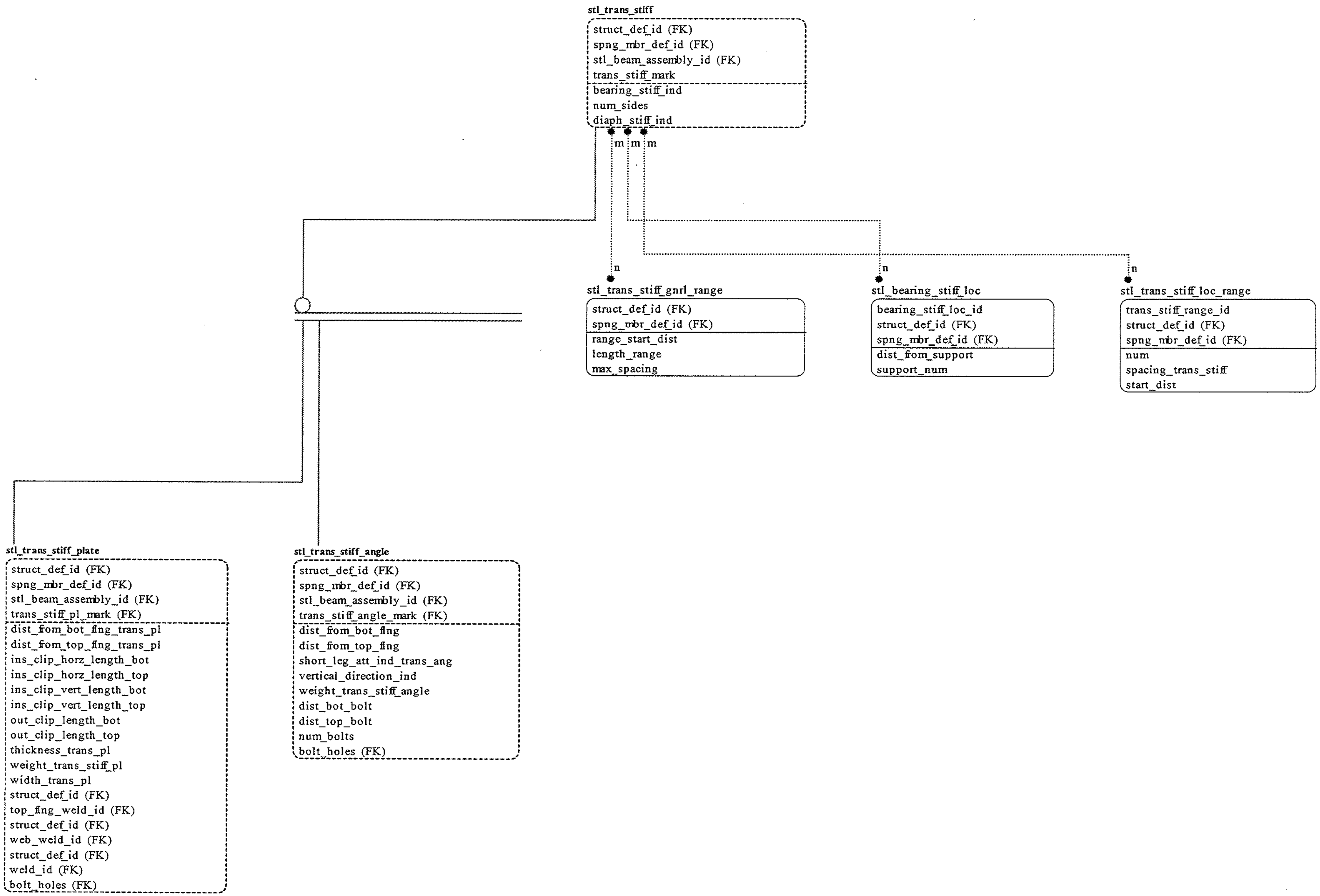
Superstructure Member Type



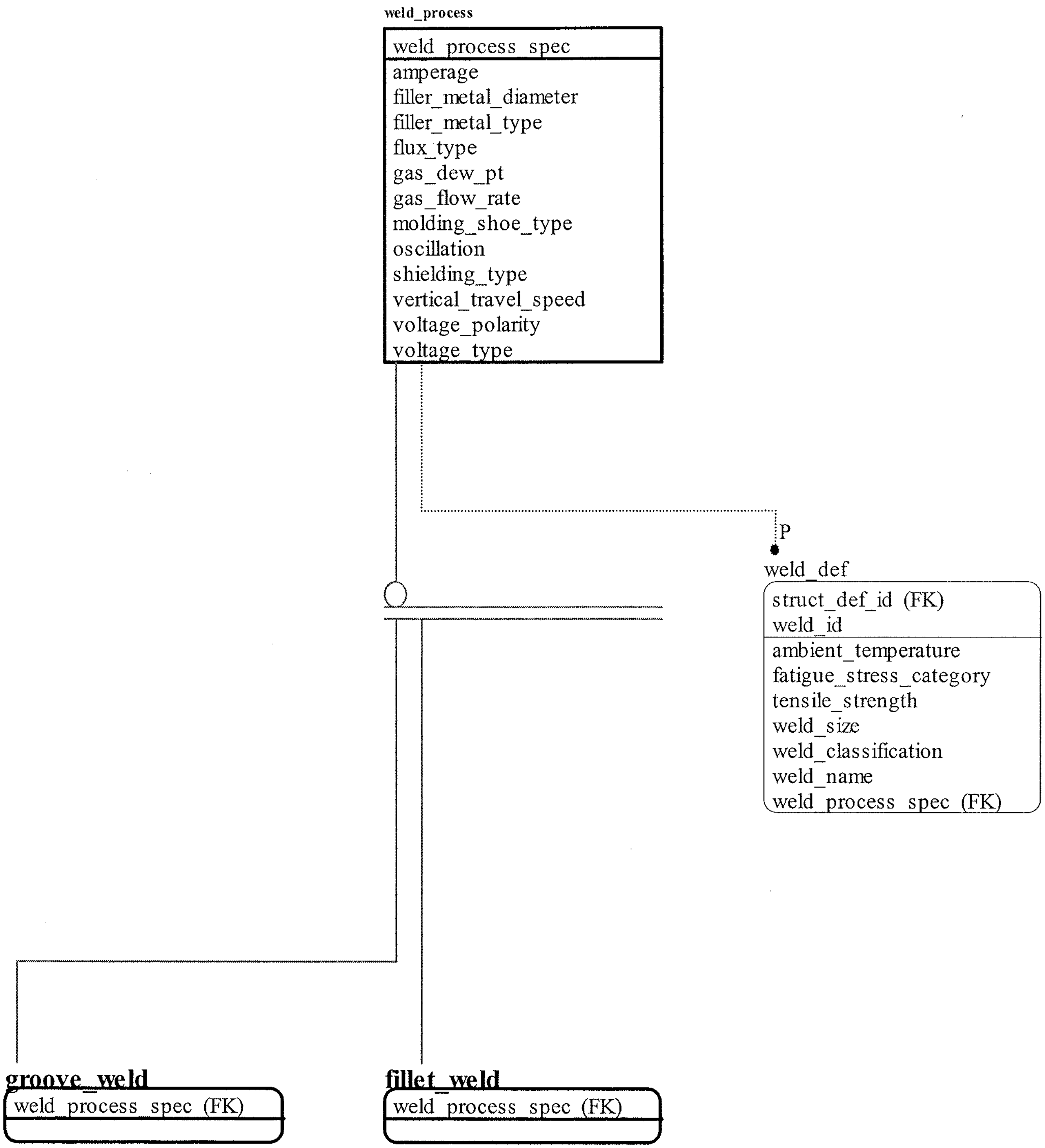
Surface Cleaning Type



Transportation Detail



Transverse Stiffener



Welding Procedure and Type

Appendix B

Problem Statement: Bridge Information Modeling for the Lifecycle

AASHTO STANDING COMMITTEE ON RESEARCH
AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS

NCHRP Problem Statement

I. PROBLEM NUMBER

II. PROBLEM TITLE

Bridge Information Modeling for the Lifecycle

III. RESEARCH PROBLEM STATEMENT

The AASHTO Subcommittee on Bridges and Structures, during its 2005 Annual Meeting, overwhelmingly passed a resolution signifying its strong support for an initiative on "Comprehensive Integrated Bridge Project Delivery through Automation". Such a comprehensive integration of advances in the automation technologies into bridge design, construction, subsequent maintenance and lifecycle management will help the State departments of transportation (DOT) manage their bridge infrastructure more effectively. This proposed research project will provide much needed bridge-relevant information modeling and data exchange capabilities in a standardized, uniform format to facilitate the incorporation of automation into the design, construction, and maintenance of steel and concrete bridges. Further, it will also help the State DOTs more effectively address issues relating to bridge durability, quality, safety, security, and lifecycle management.

For a typical bridge project all detailing, manufacturing, and construction operations require repeated manual transcribing of data from the design drawings and preparing appropriate drawings and instructions based on the interpretation and accuracy of the transcription process. This process is expensive and time consuming, and has a great potential for errors. Additionally, the otherwise advantageous use of computer-aided drafting (CAD), computer-aided engineering (CAE), and computer-assisted manufacturing (CAM) is discouraged by the dependence on the manual transcription and interpretation of data.

The primary issues to be addressed include methods of data presentation and exchange through the internet or other electronic means. 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 is 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.

IV. LITERATURE SEARCH SUMMARY

Over the last few years, various studies and workshops have been undertaken in attempts to streamline the process of designing and constructing steel and concrete bridges and to survey others internationally who have managed to accomplish varying degrees of such streamlining. The resulting findings indicate need for complete integration of 3D modeling, computer-aided design (CAD), computer-aided engineering (CAE), and computer-integrated manufacturing (CIM) in order to facilitate "better, faster, more economical" delivery of steel and concrete bridges. Documents that indicate this need include Lount (2001), Sacks (2002, 2004) Verma et al. (2001), Chen (2002), and Chen et al. (2003).

Closely related industries have already developed technologies that appear capable, "off the shelf," of significant streamlining of the processes involved in designing and constructing steel and concrete bridges. 3D – product modeling and electronic data exchange advances have been significant in aerospace (e.g., [Lockheed 2002]), automotive industries (e.g., [GmbH 2002]), and even shipbuilding (e.g., [IBM 2002]).

To date, in the U.S. these technologies have not been used in the bridge industry although they have been used successfully in other industries in the U.S. Significant potential time-savings in the envisioned project cycle have been projected, based on documented studies in related industries (e.g., [Khanzode and Fischer 2000]). Internationally the bridge industry has used these technologies to some extent (e.g., [Tamai et al. 2002]). Several U.S. bridge industry stakeholders have explored EDI (Electronic Data Interchange) in a piecemeal fashion (e.g., electronic transfer and redlining of shop drawings to expedite their approval [http://www.steelbridge.org/coldoc.htm]).

Since the current transXML effort (NCHRP Project 20-64) is not meant to realize the full promise of XML for the bridge lifecycle, further enhancements will be needed. The bridge schema development under transXML will essentially use only the existing OPIS/VIRTIS object models developed for design and rating purposes. Supplementary enhancements are needed to address concerns of other aspects such as fabrication and construction.

V. RESEARCH OBJECTIVE

The objective of this project is to develop a standard bridge data model description language, enabling the means/methods of data presentation and digital exchange through the internet or other electronic means. The model will be suitable for use by all stakeholders for design, detailing, fabrication, manufacturing, construction, inspection, maintenance and lifecycle management. Hence, once the data for a particular bridge has been established in accordance with the model, for instance initially during design, that data will be readily useable during the various stages of a bridge's life, and any software developed for use on bridges can simply work to the model, whether for design, fabrication, assembly, erection, load rating, permit rating, or maintenance functions.

Further, the proposed project will develop examples to illustrate and quantify the potential benefits of using web-friendly electronic data exchange throughout the process of designing, constructing, erecting, and operating a steel or concrete bridge structure. This project will focus on integrating the entire bridge lifecycle into a central 3D bridge "data warehouse" that is accessible (with suitable permission levels) to each stakeholder. The stages involved include: design, fabrication, change tracking, inspection tracking, virtual assembly, erection, construction management, as-built documentation, load and permit rating, and asset management.

The work is envisioned to be split into two phases:
* Phase I Objective: Identify and determine data models for the bridge lifecycle, starting with a literature review of other relevant modeling efforts, including a uniform language for electronic communication of bridge lifecycle information; quantifying the benefits they would provide; and illustrating their envisioned use in the context of testbed bridge construction/operation projects.
* Phase II Objective: Adjust and augment the Phase I data models based on an industry consensus process and use the results of this process to implement bridge schema for the bridge lifecycle. In this way a uniform language for electronic communication of bridge lifecycle information would be implemented while demonstrating its benefits for faster delivery, accelerated schedules, and lower costs.

VI. ESTIMATE OF PROBLEM FUNDING AND RESEARCH PERIOD

<u>Recommended Funding</u>: $ 750,000.00

Research Period: 48 months

VII. URGENCY, PAYOFF POTENTIAL, AND IMPLEMENTATION

We are nearing the end of an era. Bridge Engineers and contractors have relied on drawings on paper as the primary representation for centuries. But we are essentially the only industry producing 3D products that does not yet have at its core a digital product model representation and attendant electronic data exchange capabilities. Other industries have documented 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. We are overdue to do the same. Other current efforts omit major aspects of the process (e.g., recent parametric design tools and transXML omit such aspects as detailing for fabrication, construction management, erection procedures, etc). The Phase I results will provide the specifications and thus the foundation for the Phase II implementation effort. The aggregate result of the two phases will provide the key element of the IT standards infrastructure needed to accomplish a streamlined integrated process in the for steel and concrete bridge design, construction, operation and maintenance. At the same time, it will:

* Maintain the means of producing traditional 2D plans while doing it better, since they will be based on a single data repository,
* Create a uniform language for electronic communication of bridge lifecycle data,
* Utilize/build on interoperability linkages in existing software, and
* Provide the methodological foundation for adding other materials, such as timber.

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Please submit completed problem statement to the following e-mail address:

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Questions on the process can be directed to the same address or cjencks@nas.edu.

Appendix C

AASHTO HIGHWAY SUBCOMMITTEE on BRIDGES and STRUCTURES

RESOLUTION

Whereas: The AASHTO and Federal Highway Administration believe that integration through automation will help the State Departments of Transportation more effectively manage their bridge infrastructure;

Whereas: The AASHTO Strategic Plan aims at re-establishing transportation as a national priority, includes goals to accelerate project delivery, improve safety, focus on transportation security, and increase mobility;

Whereas: The Federal Highway Administration's "Vital Few" goals are to improve safety, reduce congestion, environmental stewardship and streamlining;

Whereas: The State Departments of Transportation are striving to improve the constructability, accelerate project delivery while enhancing quality and durability of bridges, and assure bridge safety, security, as well as optimized life-cycle bridge asset management;

Whereas: The States can achieve these objectives through "Comprehensive Integrated Bridge Project Delivery through Automation", which will include complete integration of 3D parametric modeling, computer-aided design and drafting, computer-aided engineering, computer-integrated manufacturing, and automated testing;

Whereas: The prevailing fragmented and piecemeal approach is far from ideal as it prevents integration of available innovative automation elements and systems that can help State Departments of Transportation achieve their abovementioned objectives.

Whereas: Recent FHWA/AASHTO-sponsored technology reviews of bridges abroad highlight the benefits of using integrated automation to achieve rapid coordinated design, construction and subsequent cost-effective life-cycle maintenance, repair and rehabilitation;

Whereas: Continued development and information sharing, as well as maintenance of this technology is needed for bridge technology to aid and advance the AASHTO Strategic Plan Goal and the FHWA "Vital Few" goals to Reestablish transportation as a national priority;

Now, therefore, 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.

Appendix D

DEVELOPMENT OF TEST SUITE FOR PILOT STUDIES

Problem Statement

Any pilot study in the area of integrated design and construction of steel and concrete bridges will need to have some basis for generalizing the results for broader use within the industry. Yet every project is different. There is a need for a principled development of a test suite of steel and concrete bridge projects that is considered to be sufficiently representative by all stakeholders. This test suite would then subsequently be made available for pilot studies aimed to furthering the use of integrated processes based around shared 3D/4D CAD and product models of the bridge structures.

Research Objective

The objectives of this research project are to develop a test suite of steel and concrete bridges by which pilot studies of integrated design and construction around shared 3D/4D product models may be conducted. Such a test suite would provide a basis for confidence in the general applicability to the bridge industry of the individual pilot study results. A findings report will include detailed illustrative examples of the use of this test suite in envisioned pilot studies.

The following preliminary set of tasks are currently envisioned

1. Review the NCHRP 12-50 work and "design of experiments" literature, regarding recommendations for systematic structuring of software test suites.
2. Survey fabricators, detailers, precasters, contractors, designers, erectors, suppliers, and owners regarding their data requirements, content of typical RFI's, etc.
3. Review and improve upon processes used in test-suite development and implementation of neutral file based interoperability in companion CIS/2 efforts in the U.S. and similar efforts (e.g., IFC-Bridge?) in Europe.
4. Review and synthesize the data needed shared among two or more project stakeholders and thus needed for interoperability studies which presumably would follow this project.
5. Define principal interoperability scenarios.
6. Organize the data around a set of progressively more complex project types and processes, where complexity would need to be defined based on the number and type (and combination) of the following that apply:
    - simply-supported spans and continuous spans,
    - various neutral file formats tried for steel and concrete data transfer,
    - straight and curved roadway geometries,
    - multiple stage-of-loading geometries,
    - for various girder types:
        i. rolled beams
        ii. plate girders, straight and curved, and

iii. tub/box girders, straight and curved
iv. precast I (bulb-tee) prestressed girders
v. precast prestressed box beams
vi. segmental and cast-in-place prestressed girders

7. Develop a set of "test bridges" and accompanying data lexicons, each of which has a core set of attributes and an optional set of attributes that makes sense for that bridge, for use in testing various interoperability scenarios.
8. Evaluate the performance of the suite in the context of interoperability scenarios (task 5) and revise as necessary.
9. Prepare a report documenting findings.

Estimate of Funding and Research Period

$250,000 Perhaps NCHRP Project 12-50, or a somewhat scaled-down version of it, could be used as an indicator.

Urgency, Payoff Potential and Implementation

Good integration and interoperability development efforts in the steel buildings area in Europe have failed in pilot project demonstrations because of over-simplification or underestimation of the stakes in a convincing pilot project. Some of these can be expected to be overcome in the US now where there are the following advantages over these EU-funded projects:
- a mature and extensive model (CIS/2 for steel, IFC more generally)
- up-front industry backing (AISC, Precast Concrete Software Consortium)
- an orderly landscape of applications (most of which participate), and
- skilled interface development by the application developers themselves.

But these are not a guarantee for success. When the applications are simple, the tendency is to focus on straightforward 'data chutes' from one application to the other. Although this may correspond to the common understanding of the workflow in the industry, it is not without pitfalls:

1 – It is possible to end up with interfaces that are limited to specific pairings of applications. The advantage of basing all interfaces on a common model is lost when X and Y make limiting 'proprietary' assumptions about what they exchange (i.e. based on an 'agreed' combination of Conformance Classes in STEP-based standards, the possible permutations of which are infinite. The resulting proprietary nature stifles innovation of workflows and may roadblock the emergence of new applications.

2 – Approaches assuming straight-through workflows may work for the average project, but how do we ascertain and defend this as a business case? Sufficiently robust test suites are needed to enable a careful study of workflows, exchange events and management aspects of a variety of steel and concrete bridge projects. Workflows seem stable and simple until a deeper inspection reveals missing links, idiosyncrasies, external events and interventions, and midstream changes. There is a danger that these group

dynamics would be ignored in a pilot demonstration. This presents the danger of alienating the pilot from real life experience.

Thus, the principal payoff would be enhanced industry acceptance of the results of pilot studies indicating improvements to the quality, cost, and delivery of steel and concrete bridges that can be obtained via integrated and interoperable processes around a shared 3D/4D product model of the bridge accessible to all stakeholders throughout the development of a project.