Bridge and tunnel modeling using 3D CAD method

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Abstract With the evolution of computer aided design tools for modeling in 3D space, significant advancements have been made to traditional methods of modeling geometry of bridge and tunnel structures. While significant advances have been made in the building and industrial sectors, the 3D modeling of transport structures, including bridges and tunnels, has been less progressed. This has been largely due to the complex road control lines, and geometry variability which tends to evolve during the design process. As a consequence, the more recent successful application of 3D CAD methods has relied on new techniques that allow the 3D model to be generated with more powerful generation tools and techniques. This paper describes some of the recent developments in these methods. The benefits of 3D CAD methods have been proven on recent projects including the Eastlink and Westgate Freeway Upgrade in Melbourne, the CLEM7 in Brisbane and other recent major infrastructures projects around the country. Construction has also realised the benefits of the 3D CAD methods. Increasingly, the designer is being requested to provide 3D geometry models to aid with the setup of survey models and to provide ease of cross checking of construction against the design models. The method increases the geometric reliability of designs, a benefit which flows into construction saving time and improving productivity. This paper includes examples of the construction benefits that have been realised on the above mentioned major bridge and tunnel projects with the aid of the new advancements in 3D CAD methods.

Introduction

This paper describes the recent development and application of three-dimensional (3D) computer aided design (CAD) methods in the area of bridges and below-ground structures over recent years.

V. Ponnampalam, H. Madrio and E. Ancich
Sustainable Bridges: The Thread of Society
AP-G90/11_006

CAD methods were introduced to the drafting world in the mid 1980's and were a major change from the traditional methods of drawing. The traditional methods relied on two-dimensional (2D) drawing methods using projected planes for describing elements. The introduction of CAD effectively transferred the tool used to create structural drawings from the paper space to the machine space, but was still effectively adopting the same drawing methods. The drawing practice remained effectively unchanged and was being undertaken by the same people using their known skills.

Some development in geometric calculations using computer methods accompanied the introduction of computers and took advantage of the greater computational power that was available, but the method for getting this information on drawings remained essentially unchanged.

Greater change occurred in the civil engineering area, where the computers were used for the design of road and drainage elements, and the simpler output for generating drawings were more easily applied to the drafting world. In the civil engineering world, much greater integration of design and drawing was quickly established and now these tools are the standard method.

Over time, the introduction of 3D computer tools, such as AutoCAD and Microstation resulted in some progressive application of 3D modeling in the structural engineering world for calculating specific complex geometries, but the applications were limited and used to the extent of obtaining information that could be used in 2D drawings. Greater application of 3D technologies was made in the buildings area and also the oil and gas area, where the geometries were more regular and involved interaction between different disciplines.

More recently, the use of 3D modeling and the direct application of the model information to drawings has become more widespread in the bridges and other civil structures industry. This has been accompanied by a demand from the construction industry for the provision of model information for construction purposes where the digital information can be used directly in survey equipment and in machine controlled applications.

Within Parsons Brinckerhoff (PB), the wider application of 3D modeling for bridges has occurred at different rates in the various Australian offices and has been dependent on local client requirements and the skill levels available. This is a developing area, however PB are effectively at the crest of change where we are leaving the traditional "adapted 2D drafting using CAD methods" to a true "3D modeling based drafting" method.

Over the next few years, it is expected the 3D modeling will be business as usual for the substantial part of our drafting works for bridges and below-ground structures.

Significant advancements in 3D modeling of transport structures

The capacity and power of computers has continued to increase at an expanding rate, and the ability to handle large amounts of information with speed is incredible; there is now no effective restriction to the use of 3D modeling as a tool.

The geometric basis for bridges and other transport structures is the road alignment. This is generated in the 3D using packages such as MX or InRoads and provides a 3D surface as the basis of the bridge.

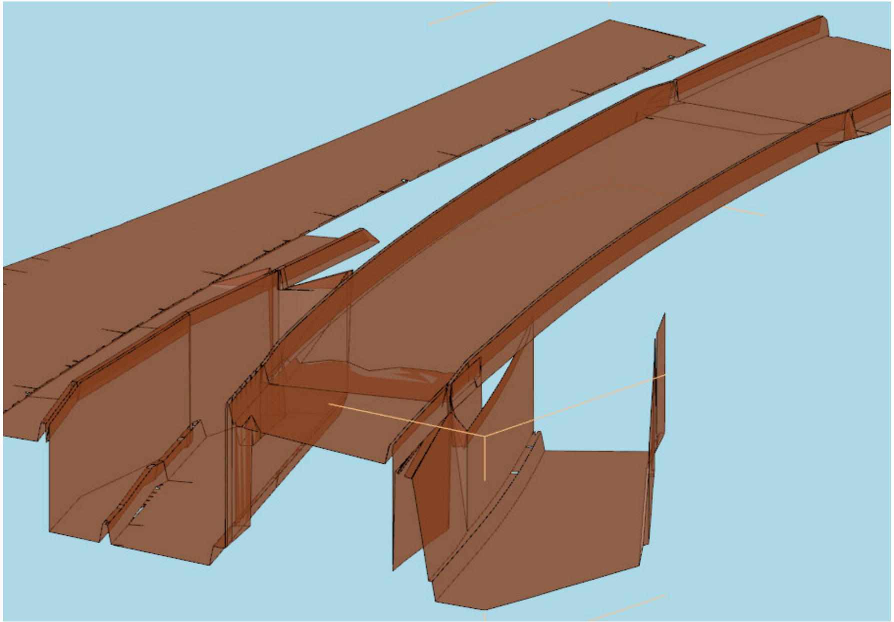


Fig. 1. Solid surfaces from road models

The solid elements of the bridge need to be fitted to this surface. Increasingly these surfaces involve complex geometry with varying width, curves, super elevation and it is an exceedingly difficult piece of work to fit solid linear elements such as beams to these surfaces using traditional drafting techniques.

The availability of 3D modeling tools which can accept the surface from the road geometry and be used as the basis for determining the bridge geometry has provided an obvious solution to this difficult and complex work. It has been a natural progression that practitioners would seek to use the available tools to solve these problems.

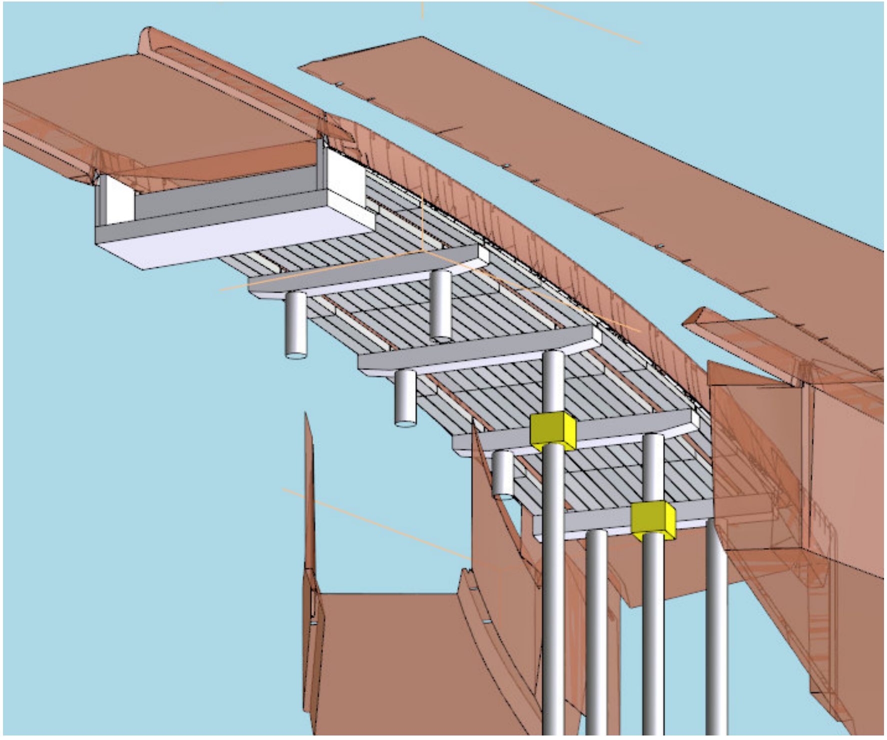


Fig. 2. Solid bridge elements fitted to road surface

Furthermore, the development of applications, such as CADPro, that permit the rapid generation of beam elements to match the surface geometry and undertake the calculations within the 3D space has meant that this process is now more automated and does not require strong first-principles application of geometry, although the continued understanding of geometry is absolutely essential. Figure 1 above illustrates the solid surface of the bridge, while Figure 2 shows the beam elements fitted to the surface. Like all computer applications, the result is only as good as the understanding of the user.

The extended use of 3D modeling to the drafting area has required the development of applications to extract data directly from the 3D model and transfer this to the 2D drawing. Various routines and macros have been developed for different purposes, and this remains an evolving area, but it is now common to extract setout data and dimensional information from the 3D models directly to drawings.

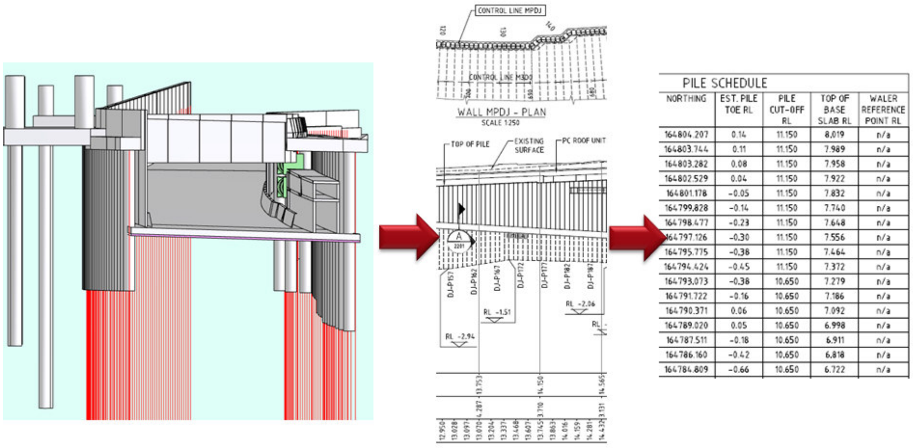


Fig. 3. Transfer of 3D information to traditional 2D drawings

The traditional drawing set formed the basis of the information used on site. This information was entirely contained on the drawings and was visual only. It is now becoming more common that the deliverable for construction is both the drawing set and the 3D model, and both are required for construction. The setout information can be contained within the model and the detailing information can be contained on the drawings, with dimensions referenced back to control lines and control points within the model.

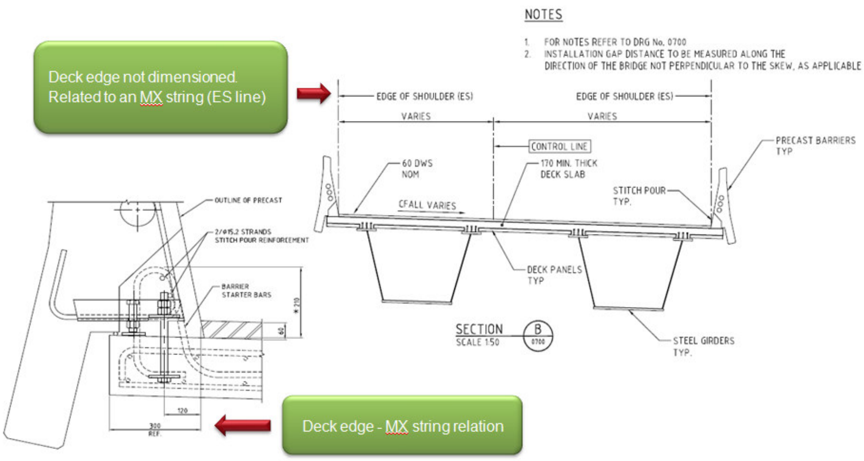


Fig. 4. Setout information provided by 3D models for construction

The issue of 3D models as a construction deliverable requires version control and must be linked to the 2D drawings. If the model is amended, it must be reissued in a similar manner as drawings are amended and reissued.

The use of the 3D structural model in this process is typically undertaken by the design drafter as the engineer has less visibility on the product. This requires recognition as part of the design process and it is essential that a strong verification process is established to ensure independent checking of the work. This is the same situation as has developed in the civil engineering area where the work is typically undertaken by civil designers. In the structural area, the 3D drafter effectively undertakes a geometric design process, and this has always been the case.

Benefits at the design stage

The use of 3D modeling can handle complex geometry in real space. This provides certainty of dimensional and set out information when assembling complex elements fitted to varying road geometry. This model must be independently verified by another drafter to ensure correctness. Subsequent use of the model as the base of all information taken for the various elements of the structure will provide certainty that it is correct.

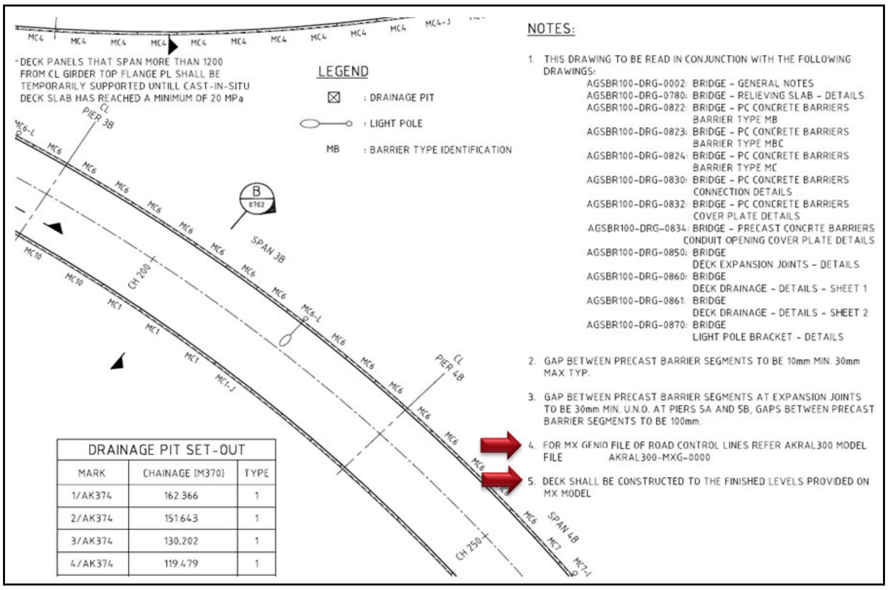
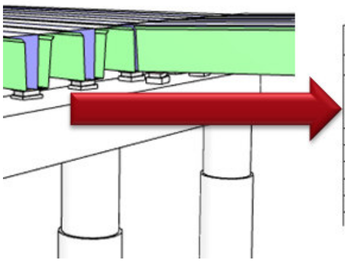


Fig. 5. Bridge deck plan, as documented, referencing 3D road model for setout information. No horizontal, vertical setout information shown.

Typically, the model is used to control the geometry, and hence there are particular identified control lines within the model that are verified to be correct. These "verified string lines" (the ES lines on Figure 4) are issued for construction and used by the constructors and other end users. The 2D drawings provide the required detailed dimensional information of structural elements and are referenced from the control lines for construction purposes. In Figure 4, the 300 dimension to the edge of the deck is dimensioned from the verified string line (ES). The adoption of the 3D model as a deliverable avoids the need to transfer complex set out information to structural drawings, (e.g. varying deck levels) and removes the risk of errors and omissions. The result is a simpler and better product. Refer Figure 5.

The use of the CADPro application enables the direct calculation of all bearing levels and taper plate dimensions for girder bridges directly from the 3D structural model. By fixing minimum deck thickness, girder depth, bearing design information and entering 3D road design, CADPro optimises deck thickness and calculates the remaining variable bearing geometry. This information is then transferred directly to the drawings. There is a greater certainty that this information is correct, and there is no reliance on a series of complex geometrical sections by the design drafter that must also go through an equally complex checking process by another drafter. Refer Figure 6.



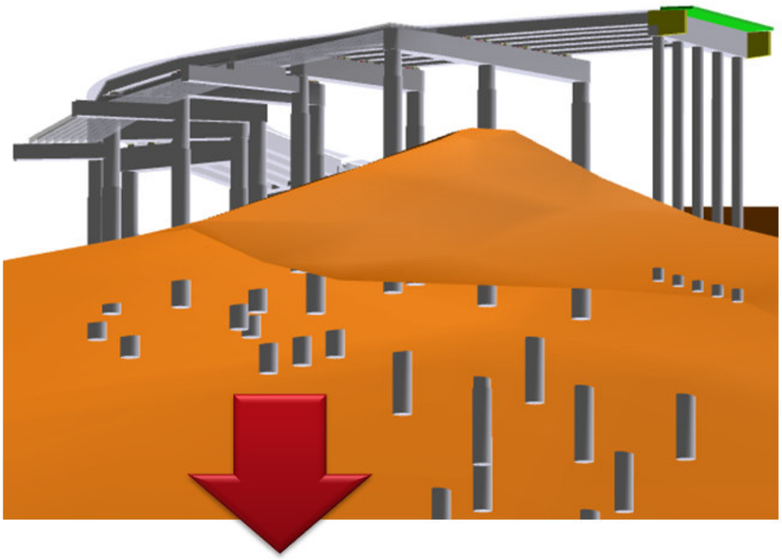
BEARING / PLINTH / BEARING ATTACHMENT PLATE SCHEDULE

PIER SETOUT					GIRDER SETOUT				
BEARING MARK	PIER SETOUT		PLINTH RL	BEARING & PLINTH ORIENTATION	BEARING / PLINTH / BEARING ATTACHMENT PLATE SCHEDULE				OFFSET
	EASTING	NORTHING			A	B	C	D	
4.1D	52925.003	161656.350	7.533	25° 44' 52"	40	66	48	22	-14
4.2D	52926.662	161655.646	7.474	25° 44' 54"	40	66	49	22	-14
4.3D	52928.712	161654.778	7.400	25° 35' 8"	40	67	50	22	-14
4.4D	52930.762	161653.909	7.327	25° 24' 14"	40	68	50	22	-14
4.5D	52932.812	161653.040	7.252	25° 12' 18"	40	68	51	22	-14
4.6D	52934.862	161652.171	7.178	24° 59' 11"	40	69	52	22	-14

Fig. 6. Bearing setout information transferred from 3D model to 2D drawing electronically

Other in-house applications enable the direct transfer of dimensional information to 2D drawings, such as the flange dimensions, skew ends, and lengths of individual girders within a deck system. On the Airport Link project in Brisbane, there are numerous girder bridges with varying geometry and hence thousands of pieces of information relating to precast girders shown in tables on the drawings. All this information was derived directly from 3D models and checked independently. A system was developed where the 2D information on the drawings was rebuilt to create a separate 3D model of the girders which was verified against the original model.

The 3D structural models exist in real 3D coordinate space and are tied to the design road geometry. Hence the inclusion of geological profiles within the overall 3D project model allows the design team to identify the relationship between structure and ground information at any location. Pile toe levels can be extracted from the model, and geological profile for design on below-ground structures can be obtained at any section. This is the closest the design team will get to modeling the below ground environment in which the structures are positioned. Refer Figure 7.



PILE SCHEDULE - CAST-IN-PLACE PILES

LOCATION	PILE NUMBER	PILE DIAMETER	TOP OF PILE LEVEL (m)	ESTIMATED PILE TOE LEVEL (m) #	HIGHEST POSSIBLE PILE TOE LEVEL (m)#	FOUNDING MATERIAL	MINIMUM ROCK SOCKET LENGTH	PILE LOADS		PILE REINF'T TYPE
								SLS (kN)	ULS (kN)	
PIER 1	P1.1 & P1.3	1200	11.750	-4.500	-	HIGH STRENGTH SLIGHTLY WEATHERED (SW) TUFF	2000	6300	9000	TYPE D
	P1.2 & P1.4	1200	12.050	-4.500	-3.000	HIGH STRENGTH SLIGHTLY WEATHERED (SW) TUFF	2000	6300	9000	
PIER 2	P2.1 & P2.3	1200	12.838	-3000	-	HIGH STRENGTH SLIGHTLY WEATHERED (SW) TUFF	1500	4900	6400	
	P2.2 & P2.4	900	12.838	-5000	-3.500	HIGH STRENGTH SLIGHTLY WEATHERED (SW) TUFF	2500	4900	6400	TYPE C
PIER 3B	P3.1B - P3.4B	900	13.850	-2.900	-2.900	HIGH STRENGTH SLIGHTLY WEATHERED (SW) TUFF	1500	3900	5100	

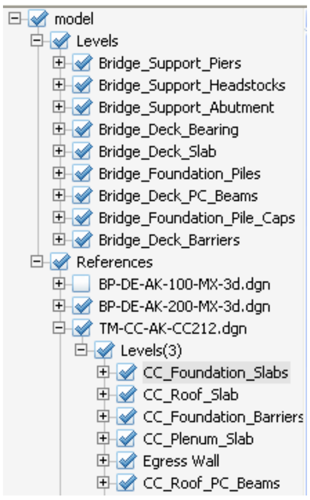
Fig. 7. Geological and bridge 3D models, showing relationship between structure and geological profile.

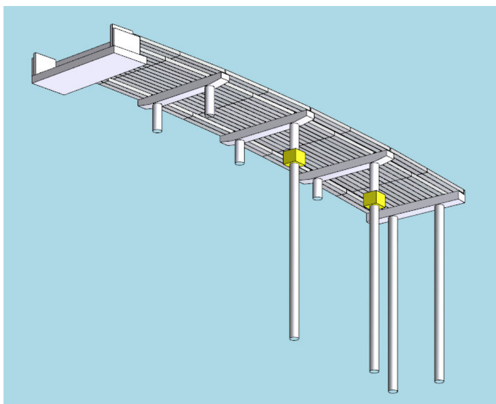
A recent experience on the Airport Link project illustrated the benefits of 3D modeling for future bridge widening. A number of recently completed Clem7 motorway bridges required widening and these bridges had been modeled in 3D as part of that project. These original Clem7 design models were available to the design team, validated against an as-built survey of the existing and then adopted by the design team as the basis for the widening designs. The widening designs are complex and involve tapering geometry and difficult level variations with varying super elevations. The ability to be able to calculate this geometry in 3D made this exercise significantly simpler than had it been done in 2D.

Another useful application is the ability to obtain the design deck thickness over the girders from the 3D models. The deck thickness can be obtained as the difference between the road surface and the top of girders and plotted as a contour of deck thickness. This enables designers to validate the design assumptions and provides certainty that the finished surfaces can be achieved.

The existence of a true 3D model of a structure permits visualisation of complex interfaces by the designer and ensures these interfaces are adequately detailed at the design stage. Extracts from the models can be placed on the 3D drawings to assist construction interpretation of the drawings.

At any stage, interactive 3D images in Portable Document Format (PDF) can be created from the model and used by the design team. These PDF images have the facility to turn layers on and off and hence enable direct visualisation of complex elements. The benefits to a design team in being able to “see” the real structure and understand the interfaces are significant. Refer Figure 8.





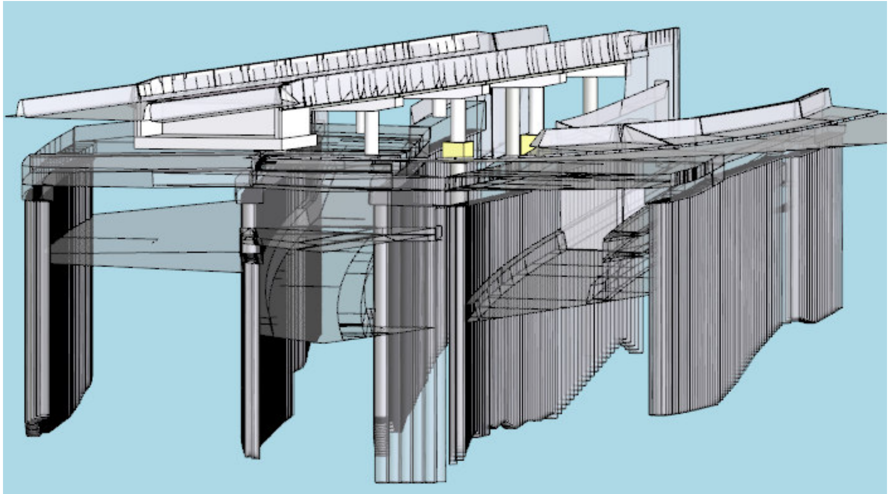


Fig. 8. The issued bridge 3D model verification PDF, showing other 3D models as "References" and all bridge structural elements "Levels" (below), bridge only and level/reference control box (above).

Complex geometrical areas can be modeled in 3D, and then the data transferred to analysis models such the finite element analysis software Strand7. In this case, the designer is able to model the true geometry of the element. This application is the normal case for design of tunnel linings (refer Figure 9) and is also used for structural modeling of beam elements.

In areas where multiple disciplines are interfaced, such as drainage elements on a bridge, the mechanical and electrical services within a cut and cover structure, or a pump room, the 3D models are integrated with the service and utility models and are used for space proofing the structure and ensuring all elements fit and can be installed.

The interfaced models are also used for safety-in-design reviews where the constructors, operators and maintainers get an accurate view of the final product and can provide input into the design to ensure constructability and operational requirements are optimised. This tool was used extensively on the Airport Link project in Brisbane for all the underground structures.

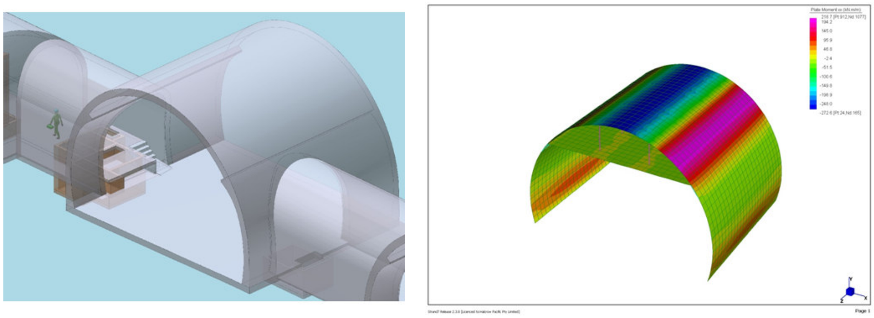


Fig. 9. Tunnel lining geometry transferred to analysis software

Similarly, to services interfaces, the 3D structural models are interfaced with the road geometry to provide true 3D topographical models of the finished road. This integrated road and structure model, with associated road furniture, has been used on a recent project to check sight distances and verify the road design.

Benefits at the construction stage

The use of 3D modeling has allowed much greater integration of design with construction (and also operations and maintenance). Many of the benefits described for the designers, are equally applicable to the construction, particularly where designers and constructors are working together to optimise design.

The best outcomes will be achieved where designers and constructors are working together, and the 3D modeling tool allows these teams to virtually build the finished product at the design stage. This optimises the design, ensures certainty for the construction site, and significantly reduces the potential for site difficulties to arise.

3D models are used to develop and illustrate stage-by-stage construction of elements such as top down construction of cut and cover structures, or progressive construction of a bridge in an operating railway environment. This enables input from the constructors and checking for access of cranes and other construction equipment.

The 3D staging models can also be linked to program activities and hence the development of 4D modeling that illustrates the construction with time. This is a useful construction planning tool, particularly for severely time constrained operations such as railway track possessions. This area of activity is referred to as “virtual design and construction” and is an emerging area. There are limited examples where this has been applied on a comprehensive basis.

The provision of a 3D model for construction purposes with verified set out information greatly assists the survey teams. The same models assist shop detailers and reinforcement schedulers. The use of the base 3D models by all parties in the design-delivery supply chain removes the risk of errors. The concept of a single model as the basis is sometimes referred to as “the single point-source of truth”. This is a significant advantage in construction.

3D model information is also used for direct input into machine-controlled operations such as road headers in mined tunnel works. This avoids the need, and associated risk of errors, for transferring data from design to drawings to machine by a series of hand-operations.

The existence of a 3D model assists the construction team to understand the structure; there is an immediate visual image without the need for having to build the image in your mind using three 2D views and turning lots of pages. The image is very easily transferred to constructors by embedding the interactive 3D PDF image in the drawing set.

3D models also permit the rapid investigation and checking of impacts of construction stage issues, e.g. level difference can be readily understood without need for complex 2D investigation. This checking can be undertaken with confidence by someone who may not have undertaken the original piece of work, i.e. there is more certainty of outcome. The existence of the 3D model provides an immediate understanding of interfaces and geometry that otherwise must be built up by a strong knowledge and understanding of numerous drawings, and where the design constraints may not be immediately apparent.

Other benefits of 3D modeling of transport infrastructure

The comments in regard to design-construction integration are equally applicable to owner-operator-maintainer involvement in the design process. Once again, the 3D model permits these parties to see the finished product and to provide design inputs. The 3D models have become a common thread in the design-delivery-own-operate-maintain supply chain; they can be shared by all parties and used for a wide range of reasons.

The development of real-geometry 3D models for structures, in addition to civil and other disciplines, enables the compilation of these models into an integrated, real-geometry model of the finished product. This has now been assembled on a number of motorway projects and includes the real-geometry lighting, signage, road furniture, line marking and landscaping, together with the structures and road geometry, and provides a full design visualisation of the completed system. This is an excellent tool, and can be used for a variety of communication and education purposes, in addition to allowing designers to verify the design outcomes. .

It is relevant to note that the integrated model described above is a real-geometry model; it is not a visualisation based on assumed and "looks-right" information. It is dimensionally and topographically correct and the nearest to achieving a virtual world.

3D models can be interfaced with a Geospacial Information System (GIS) for storage of data relating to that element. This is a very effective tool when linked to an infrastructure asset management systems.

The existence of a 3D model, whether an individual structure or a fully integrated road model, is extremely useful for future road upgrades where the models can be used as the basis for future design.

Much work is being done in the area of integrated models and linking to time and cost. There are numerous examples of 3D modeling for communication and consultation purposes. This is a large area and beyond the scope of this paper, but relevant to note that the structural modeling usefulness does not stop at the structures door.