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DESIGN FOR MANUFACTURE AND ASSEMBLY (DFMA) FOR CIVIL STRUCTURES AND BRIDGES

LIAM EDWARDS [1]

[1] Beca Ltd, New Zealand

ABSTRACT

Civil structures and bridge design and construction is ever-evolving to suit novel and quicker fabrication and construction technology, and structural engineers have now even more tools at their disposal to aid this. By utilising these new tools, together with a Design for Manufacture and Assembly (DFMA) approach, greater project outcomes can be achieved. The DFMA approach requires collaboration between design and manufacturing teams, supply chain, and numerous other stakeholders. The DFMA approach also requires a different thought process at the outset of design, and has the key principles of increasing the proportion of offsite construction, designing elements which are modular, repetitive, and for ease of manufacture and assembly. This paper considers; the benefits and challenges with adopting this approach in civil structures and bridge design; the development and use of modular and repetitive designs, the importance of a collaborative design development phase interweaving the design and construction teams; discusses practical benefits which can be realised by working in this way, such as construction programme reductions, reducing design and construction risks; and outlines how a DFMA approach can be implemented by adopting a 3D digital design approach. The paper will cover examples and approaches from large transport infrastructure projects within New Zealand, and the High Speed 2 project in the United Kingdom, Europe's largest infrastructure project.

INTRODUCTION

Over the past few decades, manufacturing and production of goods and materials and has significantly advanced with factory production and automation of processes and machinery improving and implementation on a large scale. Once initial processes are established, they are fine-tuned to increase productivity, efficiency and overall an enhanced outcome. The civil engineering industry has not seen these significant advances when compared to other industries and this has been a reason for traditional type design and construction procurement methods to still be the norm. There is continued slow growth in increasing productivity and due to this there will be a realisation that working with an alternative delivery approach can yield greater benefits for the civil engineering industry.

To adopt a Design for Manufacture and Assembly (DfMA) approach different inputs into the traditional design process are required, and by considering these alternative inputs there can be many significant benefits realised. Through personal professional experience and learnings, it is seen that traditional design and structural analysis methods can be time consuming to carry-out and have limited ability to cope with changes as the design develops, which is an ever-increasing demand being expected by this fast-changing industry. To enable the industry to improve its productivity, innovation is required. The use of DFMA is an innovative way of working, utilising the tools we have at our disposal but in a more efficient way. DFMA is supported and implemented through 3D digital design tools, and adopting a parametric design approach is one of the key tools to push the design to the limits while meeting the increasing industry demands.

In the context of civil structures and bridges, the solution to meet the demand or problem is determined in the conceptual design phase. This phase of a project is when most of the creative aspects and problem solving occurs, and thus can be considered the most important phase of the design. The conceptual design phase is when all considerations are combined, drawing on the creative and problem-solving skills of the designer, or team of designers, where initial concepts can be tested as possible solutions.

The DFMA design approach emphasises different considerations upon which the design should be based at the conceptual design phase, such as consideration of construction and manufacturing technologies and industry capability, material availability, supply chains considerations, repeatable design which can be streamlined and optimised, and seeing the design through the lens of increasing the manufacturability of the design.

DESIGN FOR MANUFACTURE AND ASSEMBLY(DFMA)

The concept of Design for Manufacturer and Assembly, or DFMA, is likely a new concept and terminology to civil and structural engineers within New Zealand and the Pacific, and below is the authors understanding of the general concept and principles of DFMA.

The general principles of DFMA design align with enhancing productivity, manufacturability, and can largely be characterised by the following points (Build Offsite, 2018):

- Standardisation of components.
- Adopting a product led design
- Offsite manufacture
- Reduction of time and man hours on site.
- Ensuring there is contractor input from the start of design
- Increased construction efficiency and less wastage.
- Developing design details which are repeatable
- Reducing construction and manufacturing errors.
- Collective design integrating all stakeholders at an early stage.

The DFMA concept is to use product design principles to develop the design of a structure, of standardised components, so that it can be combined on site in different configurations to form different arrangements. The overriding principle of the concept is to maximise off-site works and minimise on-site construction with the objective to gain benefits in programme, risk reduction, health and safety, environmental impact and quality.

Whilst DFMA is a relatively new and innovative process for civil structures and bridge construction around the world, it is not unproven in construction as the concept is used in production of buildings in around world, and to some extent in New Zealand. Almost all elements of a structure can now be manufactured offsite, and be assembled onsite.

The development of repetitive and standardised components can be done based on the use, material, and geometrical requirements of an element of a structure. The components can be systematised into families, to allow for common designs for elements with similar characteristics.

BENEFITS OF DFMA

There are significant benefits from adopting the DFMA design approach, and the level of collaboration is similar to that of Project Alliance type contracts where the contractor and designer and key stakeholders work collaboratively from the beginning of the project as a single team, however there is a much greater emphasis on offsite manufacture of elements. There are many more benefits beyond what has been identified, but these are considered the main ones. The benefits come under four different categories.

Health and Safety Benefits

- Moving workers to factory
- Less hours working on site and less manual labour
- Reduced number hazards

Quality Benefits

- Improved quality of concrete finish/steel fabrication
- More precise positioning of reinforcement/elements
- Reduced chance of defects and
- 3D modelling of all elements for clash detection

Efficiency and gains in productivity

- Repeatable: units can be duplicated for multiple bridges saving on design cost and programme
- Programme and cost savings
- Using offsite methods facilitates the process of documented learning and improvements over time, increasing productivity and safety (Build Offsite, 2018)

Reduced project risk

- Reduced risk to project schedule due to weather delays
- Less susceptible to concrete supply delays

There are project programme and therefore likely cost benefits by adopting an offsite manufacturer approach. Typically, construction programmes can be reduced significantly when compared to traditional on site construction methods. Reduction of labour on site is also a key saving. Moving workers into a controlled factory environment, which likely also improves health and safety, as well as wellbeing of workers (Build Offsite, 2018). The DFMA approach can significantly reduce the contractor's risk exposure due to the reduction in site operations.

Durability could be improved, as the manufactured process is repeated and tested, so that the optimum outputs are made. By adopting a DFMA design approach, this also adds benefits to the durability of the structures, as the repetition and standardisation of offsite construction lead to improved and more efficient construction methods which reduce the risk of errors and poor quality construction.

DFMA DESIGN PROCESS

To implement a DFMA design approach, this requires changes to the typical design process. A simple version of a typical design process for civil structures is diagrammatically shown in Figure 1 below. The high-level stages of design are; consideration and review of site constraints and requirements; identify options; then and select an option after incorporating client and stakeholder feedback.

Where the DFMA design process comes into the process is at the options phase, where standardised component and families of components are considered, and it is noted these components are likely already established components with designs with defined functions. The development of these components or families of components would typically already be established before the project had even commenced, and this is the basis of the 'product led design' approach integral with adopting a DFMA approach. Product led design, one of the general principles of a DFMA approach is where established products are used to inform the design options. Strong collaboration with the product manufacturer and contractor is required at the concept design stage to ensure the products can be successfully integrated into the design solution. In the context of civil engineering and construction, the products would be components of a bridge, or civil structure, such as retaining wall, or culvert, sign gantry, or even tunnel, and would form a portion of the greater whole.

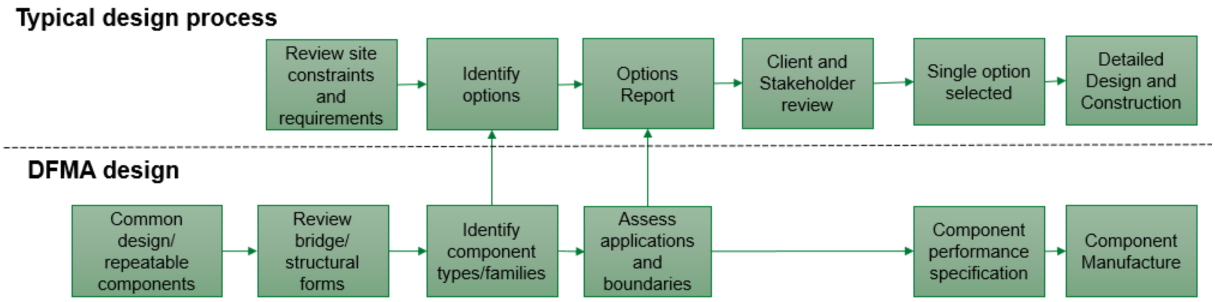

Figure 1. DFMA Design Process

DIGITAL ENGINEERING

As manufacturing technology and computer software based engineering tools are becoming increasingly available and common, the civil engineering industry is using more of these tools when developing designs. In particular, software based 3D digital models are now commonplace, and a significant portion of designs is now produced in the 3D using CAD software. A more recent innovation is software being able to create parametric 3D digital models and designs. The use of parametric modelling and 3D digital modelling is a catalyst and are some of the tools enabling implementation of a DFMA design approach for civil structures and bridges.

By applying a parametric design approach which relates key parameters through the use of parametric 3D digital design tools, civil engineering concept options can be derived rapidly, designs can be viewed in real time, in 3D and presented to clients and stakeholders.

3D digital design is also a way of generating and storing information, which can be used to review design, details, construction methodology, weights of elements, assessment of sustainability and environmental impact of the solution, cost estimates and many other criteria. All this information is needed at concept stage and by building a 3D parametric model, this information can be obtained and altered quickly from the model with the right approach to setting up the parametric model. To have ready access to this information is a critical link in the DFMA approach.

As these tools become more advanced, it enables cloud-based communication between parties to be achieved, allowing general knowledge and information to be transferred much quicker and seamlessly.

This technology provides a platform to enable effective collaboration and communication during the project bring the following benefits:

- Exchange of design parameters with architects, contractors and other engineers
- Enhancing the visualisation of the design.
- Enables output of 3D models for use by any discipline of engineering.

DFMA COMPONENTS APPLIED TO A BRIDGE

Bridge structure form and components are usually governed by the site constraints and span requirements. Short to medium span bridges, with spans approximately 55m of less the DFMA approach, do to size of components which, however also on long span bridges, the repetitive nature required to produce the bridge also suits the DFMA approach.

When considering the various elements of a bridge, the below are typical elements of any bridge, and within the table compared with the ability to easily manufacture that element offsite, and if there is a currently available standard offsite manufactured component. When considering the possibility of a standard offsite element being available, it is assumed that there is a product with defined geometry already available and a specific design to size the geometry or product is not required.

<u>Bridge components which could be easily be manufactured offsite.</u>

Table 1. DFMA application to bridge components

Bridge Component	**Standard component available in NZ**	**Ability to easily manufacture off site**
Abutment	No	Yes – precast columns, walls, steel elements, etc
Pier	No	Yes – circular piers, precast concrete, steel columns
Pier crossheads, abutment diaphragms	No	Precast formwork could be adopted with infill concrete – due to weight and size practicalities
Pile caps	No	No – typically not due to size and weight practicalities
Piles	No	No – for concrete bored piles Yes – steel or alternative driven piles
Retaining walls	Yes	Yes – There are many retaining wall systems which are modular in nature. Further, precast concrete retaining walls are also modular and are manufactured offsite.
Barriers	Yes	Yes – concrete and steel systems used widely already.
Beams	Yes	Yes – concrete and steel elements are used widely already

Bridge Component	Standard component available in NZ	Ability to easily manufacture off site
Deck elements	No	Yes – however Uncommon generally, as difficulties in creating repeatable design elements which meet overall project requirements.
Formwork permanent	Yes	Yes – however uncommon
Culverts	Yes	Yes – precast concrete steel, and HDPE, culverts are common and used widely.

Further work in developing modular and offsite products for substructures, and permanent formwork would aid in increasing the productivity of the bridges and civil structures industry. Particularly solutions which are able to meet a variety of aesthetic and stakeholder expectations.

IMPLEMENTATION OF DFMA

Within New Zealand and Australia and the UK, there is significant use precast prestressed girders, precast barriers, and steel beams, with the majority of new highway projects in these countries using these components. However, these elements still require bespoke design, but the supply chain is set up to produce these elements to standard dimensions and specifications, which does enable construction project programmes to be greatly accelerated, when compared to a full in-situ bridge superstructure.

Offsite manufactured substructure elements, such as piers, and abutments of bridges are uncommon and, if used, would be bespoke elements. As there are no standardised components currently available, initial setup costs are high and traditional in-situ construction is therefore seen as being a more efficient method of construction.

Figure 2. Offsite Manufacture of prestressed super tee girders and pier cross heads on the MacKays to Peka Peka Expressway (M2PP) project, 2017, Beca, New Zealand.

Another example of a DFMA approach is whole bridge construction offsite, then assembly onsite. The use of Self-Propelled Modular Transporters (SPMTs) to move large and heavy bridges can be used to enable whole bridge construction offsite, and then moving the finished bridge into position. This can provide significant project time savings and remove the need to have network closures if it was built onsite, in place.

'Modular' and 'offsite construction' is now common terminology, and there are a number of companies who have developed modular and/or offsite manufacture bridges. A few companies which promote and supply the types of solutions are as below:

- Mabey Bridge, UK – a modular steel truss bridge system, assembled onsite rapidly from standard elements.
- InQuick, AUS – provide prefabricated permanent formwork concrete beam bridges, with in-situ concrete to fill the permanent formwork.
- RetroBridges, UK– modular steel deck bridges – rapid onsite assembly.

Project Examples

A project in the UK being constructed by LM-JV, the HS2 Enabling Works North Contract, adopted a DFMA approach. The project developed a precast concrete permanent formwork abutment 'block' design to enable rapid construction of the abutments without the need for temporary formwork, on-site reinforcement tying etc, which removes a number of on-site steps, and reduces programme. A couple of the bridges on the project were installed using the SPMT construction method, which had significant benefits in reducing traffic congestion issues, and disturbance to the public. The majority of the structure is constructed offsite as different components and then assembled on site. The blue elements in the figure below are components of the bridge where are offsite built.

Figure 3. Offsite Manufactured modular bridge constructed in the UK using the DFMA approach and installed by SPMTs (New Civil Engineer, 2020)

Another example is the modular bridge developed by Arup (Arup, 2021) and showcased on their website, which uses precast concrete in all elements of the bridge and reportedly had significantly less time spent on both site and traffic disturbance

Challenges

As expected with any change in process or design approach, there are challenges, albeit probably fewer challenges than adopting the traditional on-site construction approach. Some key considerations which can be expected with adopting this process are as follows:

a) The attention to detail, including construction tolerances and component geometry become critical to achieving successful implementation on site, the first time. What would normally be left to the 'it will sort itself out on site' approach is no longer acceptable in a DFMA design approach. This is because the components must fit and come together as designed, and construction tolerances become critical to ensure items fit when assembled on site. However, with the use of 3D digital engineering tools, a full digital twin model can be created to check this prior to and identify any clashes before they occur on site.

b) Due to the increased repetition of elements or details on site, means one minor error could be present on the same items many times over if the error is not found at the design stage.

c) A change of client procurement and designer mind set is required to enable all stakeholders to contribute to the solution, with the designer needing to drive forward the use of a DFMA approach for it to be successful. The designer, contractor, and product supplier need to work collaboratively at the concept design stage to enable implementation to be successful -this is not a common process currently.

Future Trends

By adopting a DFMA approach, the author believes this will aid in meeting the needs of the future through increasing productivity, and with use of digital engineering tools, greater control around material usage is enabled, creating less material waste. The construction industry is undergoing a digital re-invention of itself, and this will play a role in meeting climate change and sustainability goals.

SUMMARY

Adopting a DFMA design approach from the outset of a project can help provide significant benefits to the implementation of civil infrastructure projects. The use of 3D digital engineering tools will enable the successful implementation of the DFMA approach on projects, and also increase its use in the civil engineering industry. The DFMA approach sets out to involve all project stakeholders at the concept design phase to set the right direction of the project with the focus to implement the general principles of DFMA, to bring about benefits not realised by traditional approaches. In the context of civil structures and bridges, further R&D is required to develop more standardised components for structures which will aid in project delivery through streamlining of designs and construction.

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