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A suitability analysis of precast components for standardized bridge construction in the United Kingdom

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Abstract

This paper presents the suitability of precast components for standardized UK bridges. The conventional design and construction of UK bridges is often criticized for being inefficient and unsafe as the majority of the work is carried out on-site, which requires lots of time and temporary works. The concept of Design for Manufacture and Assembly (DfMA) is employed in this study to overcome the limitations of the current bridge construction practice. First, underlying DfMA criteria for bridge construction are identified and a suitability analysis of precast components based on the identified DfMA criteria identified is conducted via an interview. Second, a case study on a bridge recently built for a highway bridge project is conducted to identify the feasibility of the potential precast components selected from the suitability analysis. The result of the case study demonstrates that the recommended precast components can be successfully used for future standardized bridges of the UK.

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Keywords: Design for manufacture and assembly, precast components, standardised bridges, suitability analysis

1. Introduction

The traditional bridge construction process is often criticized as being inefficient and unsafe [1]. The underlying reason for this is the nature of the construction where the majority of the work is carried out on-site. In fact, the design

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and construction of bridges in the UK has not been standardized or commoditized, resulting in costly and time-consuming construction practices. To address this problem, trials of off-site manufactured precast components for standardized bridge construction have increasingly been explored, inspired by the US Accelerated Bridge Construction (ABC) program [2] which utilizes a variety of precast components including piles, piers and full-depth deck slabs. However, the use of precast components in the UK is limited to a few types such as precast beams and precast piers/columns. Hence, there is a need to investigate and identify the suitability of all types of precast components for the standardization of bridge components. The concept of Design for Manufacture and Assembly (DfMA) is employed in this study to meet the needs and requirements of the bridge standardization. The objectives of this study are two-fold: (1) Identify specific DfMA criteria to be used for the evaluation of precast components for the standardization of bridge construction; and (2) Analyze the suitability of precast components based on the criteria identified. The rest of the paper is as follows. A brief review of DfMA is presented along with a classification of current and future UK highway bridges in Section 2, followed by the identification of detailed criteria for future standardized bridge components in Section 3. Section 4 analyses the suitability of precast components based on the identified DfMA criteria. Section 5 presents a case study on a bridge project adopting the DfMA approach to investigate the feasibility of the potential precast elements. Finally, Section 6 concludes with a summary of the paper.

2. Research background

2.1 Design for Manufacture and Assembly (DfMA)

DfMA is an approach to design that focuses on ease and efficiency of manufacture and assembly [3] as illustrated in Fig. 1. This approach is driven by the need to produce large numbers of high-quality products, so widely adopted in sectors such as the automotive and consumer-products industries. DfMA is the combination of two methodologies: (1) Design for Manufacture (DfM), which means parts are designed to make their manufacturing processes easier, and (2) Design for Assembly (DfA), which means the product is designed to allow easy on-site assembly. These two main blocks of DfMA are important milestones of a product development process and allocate increased percentage of time on the conceptual design phase of the product development. DfM and DfA are used in the earlier realization of technical criteria to be fulfilled for successful manufacturing and assembly of parts. There are a number of benefits of using DfMA approaches: (1) *Reduced Manufacture & Assembly Cost* - DfM seeks to reduce manufacturing costs by using fewer standardized parts and by eliminating unique parts wherever possible. This has follow-on benefits during the bridge assembly stage, because the use of standardized parts and the creation of a repetitive and familiar construction sequence can improve both the construction program and quality performance; (2) *Shorter assembly time and increased reliability* - DfMA has the potential to reduce assembly time by utilizing standardized components and rapid assembly practices. The use of digital modelling and visualization tools also allows for the simulation of assembly sequences prior to work commencing on site. This enables construction teams to become familiar with the erection sequence and methodology before setting foot on site. DfMA also increases quality and reliability by reducing variation in components and associated assembly processes, thus decreasing the chance of error on site; (3) *Shorter total time-to-market* - The development of a standardized kit of bridge parts/components with established manufacturing and assembly techniques allows designers to choose appropriate components from a library of components with well-defined design and detailing rules. This approach can create an opportunity for fast and efficient option selection during the conceptual design phase of a bridge project.

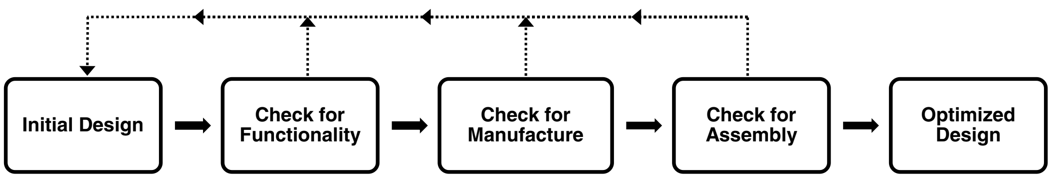

Fig. 1. DfMA procedure for a new product.

2.2 Classification of existing and future UK highway bridges

A classification was conducted using the existing highway bridge data of 5065 bridges provided from Highways England (HE) [4]. Table 1 shows the overall make-up of the existing highway bridge stock. As for structural type, slab bridges account for 43% of the highway bridges possessed and maintained by HE, followed by beam & slab bridges (30%), arch bridges (15%), box-girders (7%) and box culverts (5%). Meanwhile, as for material type, in-situ concrete (54%) is the main material used for highway bridges, followed by precast concrete (21%) and steel (15%) and brick/stone (10%). Since in-situ concrete is the main material used for slab bridges and beam & slab bridges are the second most common form of highway bridges, further analysis of the materials used for beam & slab bridges was undertaken using data from 1495 beam & slab bridges. Table 1(c) illustrates the results that precast concrete (pre-tensioned) is the main (51%) material for beam & slab bridges, followed by steel (35%) and in-situ reinforced concrete (14%). From this result, it can be inferred that precast pre-stressed beams are a primary material for the existing UK highway bridges to support bridge decks.

In order to identify the key bridge components of future UK highway bridges, a classification of near-future UK highway bridges was also conducted using a highway project, i.e. the A14 Cambridge to Huntingdon improvement scheme [5] which is one of the UK's largest road projects. The existing A14 trunk road between Cambridge and Huntingdon is well known for congestion and delays. The government has made a provision for £1.5 billion of capital investment for this scheme. This scheme is situated wholly within the county of Cambridgeshire in the East of England. It extends from Ellington, on the existing A14 on the western outskirts of Huntingdon, to the Milton junction on the Cambridge Northern Bypass. It includes both new highway construction and the widening and improvement of existing highways over a total length of 34 km (21 miles). If the development consent for the proposed scheme is granted, construction of the main works would be expected to commence in 2016 and continue for a period of approximately 3.5 years to 2020. There are 28 new bridges planned for this project. Table 2 shows the classification of the planned new bridges according to structural and material types. It can be seen that beam & slab bridges (86%) are the dominant type of the bridge expected to be built within 3 years. As for the material type, precast concrete components have been selected for the primary structural elements of these bridges. From the classification of the current and future UK highway bridges, precast components become a primary element in the UK bridge market. In the following section, DfMA criteria are determined to identify suitable precast components for standardized future UK bridges.

3. Research approach

General DfMA criteria are first identified based on underlying DfMA requirements which are widely adopted in the manufacturing industry. Then, specific criteria to be used for the evaluation of precast components for the standardization of bridge construction are developed based on the general DfMA criteria identified.

Table 1 Classification of existing highway bridges:(a) structural type, (b) material type and (c) material type within beam & slab bridges

(a) **Structural Type**		(b) **Material Type** (Primary)		(c) **Material** (Primary) **Type**	
Slab	43%	In-situ Concrete	54%	Precast Concrete	51%
Beam & Slab	30%	Precast Concrete	21%	In-situ Concrete	35%
Arch	15%	Steel	15%	Steel	14%
Box-girder	7%	Brick / Stone	10%		
Box culver	5%				

Table 2 Classification of near-future bridges according to structural and material types

Structural Type		**Material** (Primary) **Type**	
Beam & Slab	24 (86%)	Steel	4 (14%)
Arch	1 (3%)	In-situ concrete	3 (11%)
Box culvert	1 (3%)	Precast concrete	21 (75%)
Cable-stayed / Suspension	2 (8%)		

3.1 Identification of general DfMA criteria

A DfMA approach for product development aims to simplify the product structure and reduce manufacturing and assembly costs through enhancements in the design process [6]. Four common criteria for DfMA are listed below:

(1) *Simplification in design* - In the design phase, each bridge component should be checked using the following set of questions: Can the part be combined with another part? Can the part be standardized? Can the function be performed in another way? If so, a great deal of cost can be saved without compromising quality through lower material usage, reduced inventory and assembly costs.

(2) *Reduced number of parts* – Reduced the number of parts allows for a simplified design as fewer fabrication steps are needed during manufacturing. In addition, as the number of assembly parts decreases, the risk of errors during assembly decreases, therefore providing a more seamless assembly and disassembly process.

(3) *Standardization of commonly used parts and materials* – Standardization of commonly used parts and materials will decrease inventory costs while increasing the efficiency of handling and assembly operations. Furthermore, product development experimentation is not required, resulting in additional time and cost savings.

(4) *Ease of orientation, handling and assembly of parts* - Assembly parts should be designed to minimize movement, rotation and/or any other non-value-adding manual efforts for a saving in time and cost.

3.2 Development of detailed DfMA criteria for bridge components

Details of UK bridge construction are here investigated focusing on three aspects most relevant to DfMA as follows:

(1) Connection details - Connections are important parts of a bridge with regard to assembly time and cost. The connections between different precast concrete bridge components can be time-consuming to assemble and difficult to automate. Complexity in connections between bridge components can be reduced by minimizing the number of connections and adopting an efficient joining and fastening system.

(2) Repeatability of components - Manufacturing processes have to be designed and developed so that a standard component can be reliably reproduced time after time, within required manufacturing tolerances. This is a process often referred to in manufacturing as 'repeatability'. The same component types can be used in different projects and thus a standardization often results in large economic cost benefits. The standardization in the manufacture of bridge components can be achieved by designing casting moulds for producing various component types with a high degree of repeatable accuracy. Moreover, if manufacturing processes are standardized, then handling and assembly operations can be conducted more effectively.

(3) Suitability for manufacture - A design for manufacturability of bridge components is the process of proactively designing products to 1) optimize manufacturing functions such as fabrication, assembly, test, procurement, shipping, delivery, service, and repair, etc. and 2) assure the best cost, quality, reliability, regulatory compliance, safety, time-to-market, and customer satisfaction.

Table 3. Specific DfMA criteria for bridge components

General criteria	Manufacturing characteristics	Assembly characteristics	Desired characteristics
1. Simplification in design	Number of fabrication steps	Number of assembly steps	Few
	Level of manufacturing complexity	Level of assembly complexity	Simple
2. Number of parts	Number of parts for manufacturing	Number of parts for assembly	Few
3. Standardisation of commonly used parts and materials	Are the parts standardized and made of common materials?		Standardized and commonly used materials
4. Ease of orientation of parts and handling	Properties of parts (e.g. size and weight) to be easily placed and manufactured	Properties of parts (size and weight) to be easily placed and assembled	Easy to handle parts and easy to manufacture and assemble
5. Ease of joints and fasteners	Number of joints and fasteners for manufacturing	Number of joints and fasteners for assembly	Few

Detailed DfMA criteria were developed based on the DfMA criteria for bridges investigated above. Table 3 shows the specifications of the detailed criterion for each general DfMA criterion in terms of the manufacturing and assembly of bridge components. First, two requirements, 1) number of steps and 2) level of complex, were developed as the DfMA criteria with respect to the first general criterion '*simplification in design*'. The number of fabrication and assembly steps should be minimized as much as possible, and these steps should be simple. Second, the number of parts for both manufacturing and assembly processes should be minimized whilst meeting all functional requirements. Third, the components and materials selected should be standardized and common so that any further experiments on the components are not required. Fourth, the properties of the components (e.g. size and weight) should ensure that they are easily handled and placed during manufacturing and assembly processes. Lastly, steps of jointing and fastening should be kept to a minimum and the process should be as straightforward as possible.

4. Suitability analysis of bridge precast components

An evaluation of the most popular components, precast beams, was first performed to identify the suitability of precast beams for future standardized bridges. Table 4 shows the precast beams available in the UK market along with notes on their form and span range. Here, the suitability refers to the level of conformity to the DfMA criteria identified in Section 3.

Table 4. Current precast beams used in the UK [7]

Beam	Section	Form of deck	Economical span range (m)	Depth range (mm)
TY-beam		Solid slab	4-17.5	400-850
Inverted T-beam		Solid slab	5-17	380-815
TY-beam		Beam & slab	7.5-17.5	550-850
Y-beam		Beam & slab	14-31	700-1400
SY-beam		Beam & slab	27-45	1500-2000
M-beam		Beam & slab	16-30	720-1360
U-beam		Beam & slab	14-34	800-160

An interview was conducted with a senior engineer from the largest precast beam supplier, Banagher Inc. [8] as the means of evaluation. Two measures were used for the evaluation: (1) popularity and (2) suitability with respect to the DfMA criteria identified in Section 3. In the interview, the respondent was asked to assess the popularity and suitability of each precast beam using five options (Very High (VH), High (H), Medium (M), Low (L) and Very Low (VL)). Six types of precast beams were chosen as possible options based on their availability in the UK market for each bridge span of 10-20m and 20-40m, respectively. Table 5 shows the popularity evaluation results. TY and MY beams turned out to be the most popular components for bridge spans of 10-20m while W beams are the most popular choice for bridge spans between 20-40m followed by Y and U beams. Tables 6 and 7 detail the suitability results evaluated based on the DfMA criteria. Solid box, TY, Y, and MY beams are evaluated as highly standardized and simple in terms of manufacturing and assembly for spans of 10-20m, while Solid box, Y, U and W beams are evaluated as suitable components for spans of 20-40m. Based on this evaluation, four precast beams (Solid box, TY, MY and Y beams) and three precast beams (Y, U and W beams) were selected as potential DfMA components for spans of 10-20m and 20-40m, respectively for future standardized bridges.

In addition, a suitability analysis of 8 other precast bridge components currently manufactured was also performed. The assessment was conducted using a qualitative evaluation since these precast components are not as popular as the precast beams and fewer types are available in the market. Two criteria were used for the evaluation, (1) simplicity in design and manufacture, and (2) availability. Table 8 presents the qualitative result showing that seven the precast components out of eight elements (edge beams, parapets, permanent formwork panels, cill beams, piers/columns with crossheads, abutments and precast box panels) have potential as standardized DfMA components for the future UK bridge construction.

Table 5. Evaluation of precast beams based on popularity

Span 10-20m	Popularity	Span 20-40m	Popularity
Solid box beam with in-situ infill deck	M	Solid box beam with in-situ infill deck	L
TY-beam with in-situ infill deck	VH	U-beam with in-situ solid deck	M
U-beam with in-situ concrete solid deck	M	Y-beam with in-situ solid deck	M
Y-beam with in-situ concrete solid deck	M	SY-beam with in-situ solid deck	L
M-beam with in-situ concrete solid deck	VL	M-beam with in-situ solid deck	VL
MY-beam with in-situ infill deck	H	W-beam with in-situ solid deck	VH

Table 6. Evaluation of precast beams based on the DfMA criteria for spans 10-20m

	Simplification of design	Reduction of parts	Standardised parts	Ease of handling
Solid box beam	VH	VH	VH	VH
TY-beam	VH	VH	VH	VH
U-beam	M	VH	VH	M
Y-beam	VH	M	VH	VH
M-beam	M	M	VH	M
MY-beam	VH	VH	VH	VH

Table 7. Evaluation of precast beams based on the DfMA criteria for spans 20-40m

	Simplification of design	Reduction of parts	Standardised parts	Ease of handling
Solid box beam	VH	VH	VH	VH
U-beam	VH	VH	VH	M
Y-beam	VH	M	VH	VH
SY-beam	M	M	VH	VL
M-beam	M	H	VH	VH
W-beam	VH	VH	VH	M

5. Case study – Soar Floodspan Viaduct bridge

A case study on a bridge recently built for the A453 bridge widening project located in Nottingham [9] is presented to identify the feasibility of the selected precast components. The bridge delivered by Laing O'Rourke was selected since the bridge adapted the DfMA concept which is the main theme of this study. The bridge is a five span viaduct, with an overall length of approximately 96m and a width of 13m, and the new viaduct was aligned to the existing bridge in such a way as to maintain a nominal 6.3m wide central reserve of the dual carriageway and with a flood span arrangement identical to the existing bridge with five equal spans of 19.2m each as shown in Fig. 2. The precast components employed for the bridge construction are precast (1) Y beams, (2) edge beams (YE beam), (3) crossheads (pier caps), (4) piers, (5) abutments, and (6) cill beams. Among the bridge elements, one bridge element, the precast crosshead, is investigated in detail to identify its feasibility as DfMA component with respect to installation on site.

Fig. 3 shows the interface details between the precast crosshead and the precast pier. The interface between the precast crosshead and supporting piers required accurate setting out of both the reinforcement projecting from the top of the pier and the void cast in the cross head (through which the reinforcement passes). The connection was achieved through the use of a laser cut template produced from a 'digital engineering' model. A full-scale mock-up was also made prior to the actual installation to understand the potential issues with cumulative tolerances. The link detail was also amended to prevent clashes. This DfMA approach of digital bridge construction allowed for a successful pre-assembly manufacturing in factory and installation on site, indicating that proposed DfMA precast components can be successfully used in near future bridge construction in the UK.

Table 8. Qualitative evaluation of other bridge precast components

Component		Qualitative Evaluation	
		Simplicity in design and manufacture	**Availability**
Superstructure	Precast edge beams	These components are highly standardized and designed with their counterpart components, precast beams, indicating simplicity in design and manufacture.	TYE, MYE and YE beams
	Precast parapets	These components are normally designed with precast edge beams so that the design of these components can be easily conducted.	Parapets with TYE, MYE and YE beams
	Precast permanent formwork panels	These components are mostly rectangular with a constant thickness, resulting in simple design and manufacturing.	Panels with TY, Y, U and W beams
	Precast cill beams	These components have simplicity in its design and manufacturing. The use has been validated in recent projects such as the A453 bridge project.	Few
Substructure	Precast piers/columns and crosshaeds	These components have simplicity in its design and manufacturing. The use has been validated in recent projects such as the A453 bridge project.	Few
	Precast abutments	These components have simplicity in its design and manufacturing. They have been designed and manufactured using the shell-type structure, and the use has been validated in recent projects such as the A453 bridge project.	Few, shell-type panels
	Precast retaining walls	The design and manufacture of these components are not as simple as the other precast bridge components.	Single, double heel solid type and shell-type
	Precast box panels	These components have simplicity in its design and manufacturing.	Solid box and Shell-type panels

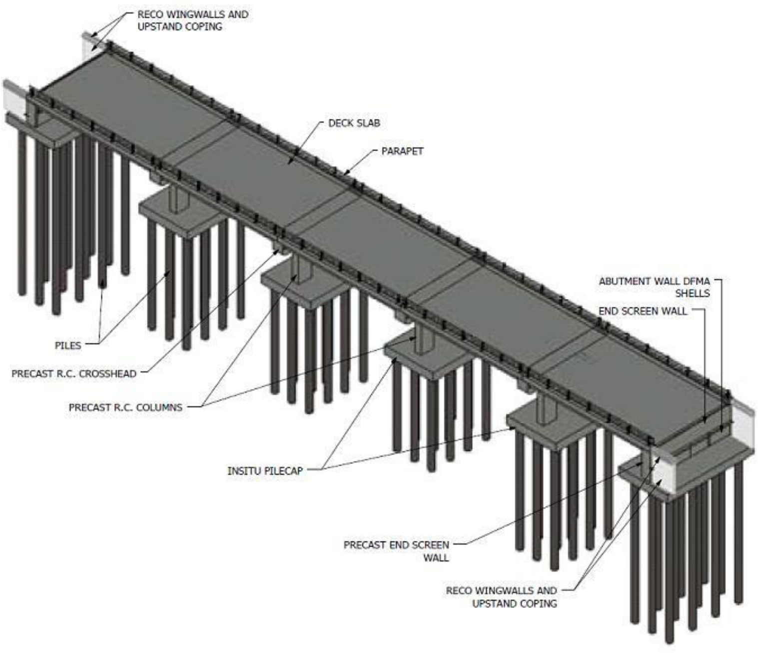

Fig. 2. 3D view of the A453 widening project Soar Floodspan Viaduct bridge (*Image from Laing O'Rourke*)

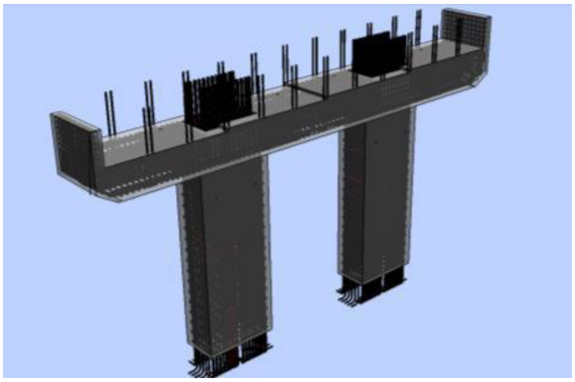

Fig. 3. Interface details between the precast crosshead and the precast pier (*Image from Laing O'Rourke*): (a) 3D view of the precast crosshead and precast piers; (b) A photo of the connection between the two components

6. Conclusion

This study identified and selected precast components suitable for future standardized bridges in the UK. The concept of Design for Manufacture and Assembly (DfMA), popularly used for product development in the manufacturing industry, is employed to achieve the future standardization of UK bridge construction. First, specific DfMA criteria were developed to evaluate precast components for the standardization of bridge construction. Second, a suitability analysis of precast components based on the DfMA criteria identified was performed by conducting an interview. 13 precast components (6 precast beams and 7 other components) were recommended from the suitability analysis for future standardized bridges of the UK. The result of the case study demonstrated that the DfMA-assisted digital bridge construction, where pre-assembly manufacturing is implemented prior to actual manufacturing and assembly, led to a successful installation on site, indicating that the DfMA precast components proposed can be successfully used in near future bridge construction in the UK. Although the outcome of this study may be limited to the use of the UK bridge construction sector, the approach used in this study for the suitability analysis using the DfMA criteria can be used for standard and modularized bridge constructions in other countries.

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