Reconstruction of a Ukrainian road bridge by use of 3D printed minimass beams

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Abstract

Minimass is an open "truss-type" concrete and steel beam which creates stiffness and strength through axial compression and tension. The new technique of 3d concrete printing unlocks the potential of this design by allowing the fabrication of these beams at a fraction of the cost of traditional means: no formwork, minimal steel reinforcement, low carbon. The rural bridge in Ukraine is located in Kherson Oblast. The original span was destroyed during the war. The new bridge deck is designed with prefabricated minimass beams, lattice slab concrete panels between the beams and a cast in-situ top slab. The combined use of printed and in-situ concrete leaves various technical issues to be studied, for example the construction joints shall be designed to ensure 100 years' service life. The minimass beam structure is estimated to reduce the material quantities and embodied carbon by 40% in this case.

Keywords: minimass™ beam, printed concrete, external posttensioning, composite truss

1 Introduction

Road and rail bridges in Ukraine have suffered damage and destruction throughout the period of fighting in the country, as they are a key element of transport logistics. According to the State Agency for Reconstruction and Development of Infrastructure in Ukraine [1], 346 bridges have been destroyed (up to the end of June 2023). 41 bridges were re-built during 2022 and it is expected that 40 locations will be re-built during 2023. In addition, the Reconstruction Agency has implemented temporary crossings at a further 85 of these locations. One of these temporary crossing locations was identified by the State Agency for Roads as being a suitable location for the construction of a new type of bridge, to act as a pilot which demonstrates the practical application of 3D printed concrete for infrastructure.

The State Agency for Roads has engaged with a local non-profit organisation called Team 4 UA, who have started to introduce 3D printing for concrete to the Ukrainian market. Net Zero Projects (NZP), working with COBOD International and Rambøll, has developed a design for a new bridge, using the principles of minimass beams, described herein.

The bridge is located just north of the village of Starosillya, Figure 1, at km 54+397 of the road T-22-07 / T-04-03 / Vysokopillia – Velyka Oleksandrivka – Beryslav, in the Kherson Oblast.

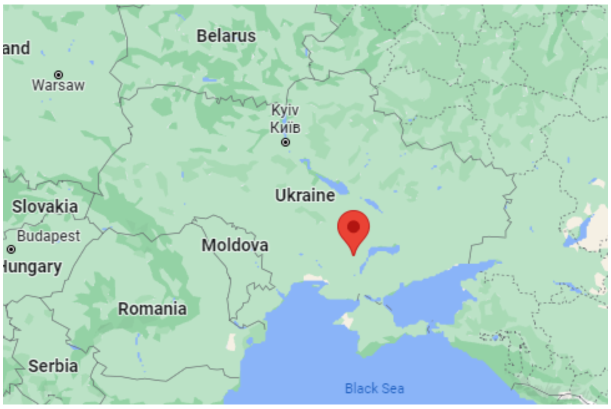

Figure 1: bridge location in the context of the country of Ukraine

The bridge supports a country road, with a single lane in each direction, passing over a narrow tributary to the Inhulets river. The original bridge was built in 1967 and the date of the most recent (pre-war) bridge inspection was November 2013. It was a two-span structure, where each span was 4.3m in length, built using precast concrete hollowcore slabs. The total length of the structure, including the embankments, was 15m, refer to Figure 2. The width of the roadway was 8.5m with the total width of the construction, including footpaths and handrails being 11.1m.

Photos from the 2013 inspection show a bridge in operational condition but with signs of significant corrosion, Figure 3 and Figure 4.

Figure 5 and Figure 6 show the bridge after it was destroyed, with the original structure having collapsed into the water. A temporary crossing was built to reinstate the road but the waterway remains blocked by the rubble and debris.

The new bridge design proposed by the team is to build a single span structure, without the original central support. As flood and water traffic information was not available, it was considered prudent to assume a design which fit within the structural envelope of the previous bridge. This would mean a target structural depth of 750mm, refer to Figure 7. The width would be slightly increased, to 12m, to meet more recent Ukrainian road construction standards.

Minimass is the name of a design approach developed by NZP which aims to create bending structures – typically beams – with optimised geometries, using 3DCP. A full description of the design approach can be found elsewhere [2] but the principles are to use primarily axial tension and compression, in a "truss-like" manner, instead of simply relying on material bending strength. A concrete top chord resists compression and a steel cable bottom chord resists tension. The steel cables (standard post-tension tendons) are separated from the top chord by concrete webs, with the arrangement of webs and the geometry of the cables defined according to the applied loads. In this case, the concrete top chord is reinforced with mild steel reinforcement, so it behaves like a beam-column, not just an axial compression member.

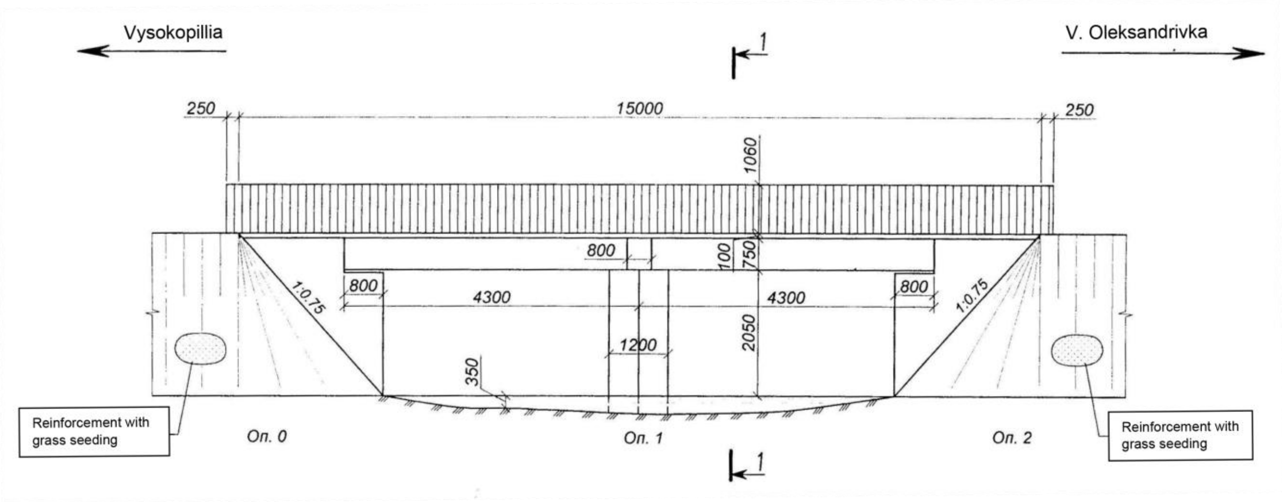

Figure 2: original bridge elevation

Figure 3: original bridge showing two spans.

Figure 5: destroyed bridge blocking the waterway.

Figure 4: original roadway with kerbs and handrails

Figure 6: bulldozed temporary crossing.

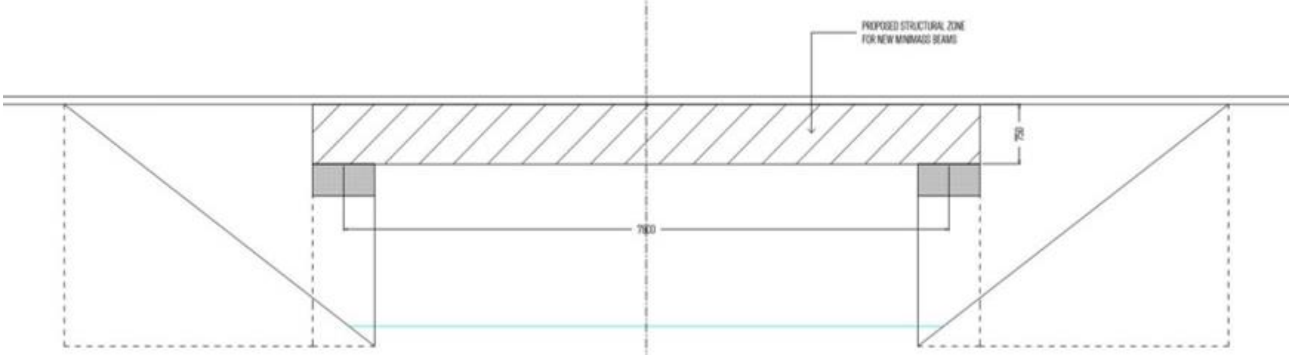

Figure 7: proposed bridge span

Figure 8: render of the completed bridge

The original inspiration for the development of the minimass approach was as a method of reducing embodied carbon, as well as cost for structures.

Indeed, by generating potential embodied carbon savings of up to 50 - 70%, the next generation of 3DCP structural elements will provide designers with a new set of options for more sustainable designs. However, in the context of the political situation in Ukraine, the savings in embodied carbon are not the primary motivation.

2 Structural design approach

The new bridge, see Figure 8, was designed according to Eurocode 2 [3], which is accepted within Ukraine as part of a legitimate framework of design standards. Prior to final construction sign-off, to be carried out by a registered local engineer, the design will be reviewed against Ukrainian bridge codes as a double check. The design was carried out by NZP but with oversight and input from the engineers in the bridge department of the Rambøll office in Copenhagen.

As would be typical for a short, single span bridge, the live load tends to govern the design, with the group loading associated with Load Model 1 defining the beams and Load Model 2 (local point loads) defining the design of the slab.

The proposed solution is a series of primary beams spanning the length of the bridge, with a thinner slab spanning between the beams. The beam spacing is set to 1.5m c/c, resulting in a total of 8 beams within the 12m width. The preference is to avoid temporary formwork, so prefabricated lattice slabs (also known as "omnia deck" or "filigran") are laid between the prefabricated beams. This provides permanent formwork for an in-situ topping slab and a safe working platform across the water during construction. If this were a conventional precast concrete solution, the beams would be designed to work compositely with the slab (in the permanent condition), creating an efficient T-beam design in cross-section. The minimass approach is to use the same principles of efficient composite construction but with a 3D printed primary beam instead of a conventional precast I-beam. As the project is looking to maximise the use of 3DCP, the decision was made to also 3D print the lattice slab elements, although these could just as easily be sourced from conventional precast suppliers.

The design life of the structure is expected to be 100 years, in line with the recommendations of the Eurocode. Subsequently it became clear that the Ukrainian codes would permit a design life of 70 years, although the decision was made to retain 100 years as the target.

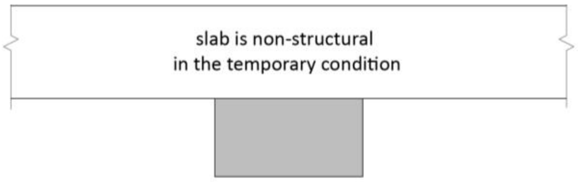

Figure 9: principle of temporary condition (cables not shown)

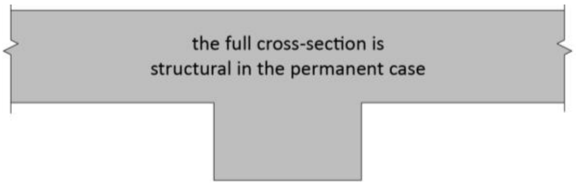

Figure 10: principle of permanent condition (cables not shown)

The early focus on design life and corrosion resistance was important in terms of preliminary sizing and feasibility, with particular reference to the 3D printing method. Maintaining adequate cover to mild steel reinforcement is critical as well as considering how best to protect the external post-tension steel cable.

This design approach then followed the typical calculation steps that would be familiar for conventional concrete structures, including checks for bending strength, shear force, torsion resistance, vertical displacement etc. Both temporary and permanent conditions were considered (Figure 9 and Figure 10). All aspects of strength and stability have been confirmed, although there are special design issues to consider. The structure is therefore considered to fulfil the demands of the Eurocode for strength and stiffness.

With regard to robustness, as the beams are statically determinate, the design allows for the accidental failure (e.g. cutting of the tendons) of one beam. In this scenario, the deck is designed to redistribute the accidental load case forces to the remaining beams making sure that the bridge will not fail. The defective beam can then be repaired, returning the bridge to full capacity.

In terms of durability, a high degree of quality control / assurance at the prefab shop can be carried out to provide adequate concrete cover to the reinforcement. On site, the in-situ works have to be followed carefully, so that the new issues for printed concrete, described below, are dealt with properly.

The durability of the cables is provided by achieving a protection level of PL2, as defined by fib bulletin 33 [4]. This is where the individual greased and sheathed tendons are then enclosed in a single outer duct, which is filled with either grease or wax. This approach – by specifically avoiding grout in the outer duct – allows the individual tendons to be re-stressed or replaced as part of a future maintenance regime.

3 Printing of concrete

3D Concrete Printing (3DCP) techniques have developed very much over recent years, with research taking place widely [5–9]. Accurate, digital control of the X,Y,Z position of the printer nozzle can be achieved with either a robotic arm set-up, or a gantry style printer. This approach aims to eliminate, or replace traditional timber or steel formwork, generating valuable cost savings and providing a means of creating complex geometries, hitherto cost prohibitive. Avoiding traditional formwork, which is often used only once or a few times, also saves material and the associated CO2e.

The authors do not expect 3DCP to replace all types of concrete construction. Indeed, the methods used for standard prefabricated elements, such as piles, hollowcore slabs etc are very efficient and not necessarily improved by the printing process. Equally, large pours on site are much faster with conventional pump equipment than with a printer. However, the boundaries of what is structurally possible with 3DCP are only now being pushed.

The issue of reinforcement for 3DCP is significant, with much research dedicated to this specific aspect [10–13]. Rebar can only be applied in a certain restricted manner. It can be placed along and across the print path (during the printing process) but it cannot be placed through the print path. Therefore, traditional rebar cages with bars in all three orthogonal directions are not currently possible. However, the minimass approach aims to embrace the geometrical freedom of the technique, whilst respecting the constraints of the reinforcement requirements.

The minimass beam is printed on the side, with the print “bead” defining the outer perimeter of the shape, much like a permanent formwork. By layering the print beads with a thickness of 30mm, a 3-dimensional shape is built up, with an internal cavity that can take any required reinforcement (see Figure 11), prior to being infilled with pumped, or printed concrete.

Figure 11: reinforced, 3D printed concrete.

These techniques can be economically applied to moderate span bridges but it remains to be seen whether 3DCP will be suitable for very large bridges or structures.

4 Embodied carbon comparison

The authors have considered the embodied carbon of the new bridge design, compared with rebuilding the previous bridge design (as closely as possible). It would be possible to re-build this bridge in a number of different ways, each generating a different embodied carbon profile. However, as this project was specifically focused on the design of a 3DCP bridge, the other options have not been included in the carbon comparison.

Table 1: estimated embodied carbon for 3DCP minimass bridge.

	concrete mass [kg]	**mix design**	**CO2e** [kg/kg]	**rebar** [kg/m^3]	**mass rebar** [kg]	**mass PT** [kg]	**Total CO2e** [kg]
3D printed beams	12960	D.fab	0,142	260	1404	424	4186
3D printed slabs	14640	D.fab	0,142	200	1220	0	3543
in-situ slabs	54720	RC40/50	0,178	150	3420	0	13844
end abutment padstones	9139	RC35/45	0,161	200	762	0	2385
end abutment walls	78326	RC20/25	0,121	100	3264	0	13394
end abutment foundations	45850	RC20/25	0,121	-	0	0	5548
totals	**215.635**				**10.069**	**424**	**42.900**

Table 2: estimated embodied carbon for rebuild of previous bridge design.

	concrete mass [kg]	**mix design**	**CO2e** [kg/kg]	**rebar** [kg/m^3]	**mass rebar** [kg]	**mass PT** [kg]	**Total CO2e** [kg]
Precast slabs	103200	RC40/50	0,178	20	860	675	20455
roadway slab	40752	RC35/45	0,161	50	849	0	7580
end abutment padstones	9139	RC35/45	0,161	200	762	0	2385
end abutment walls	78326	RC20/25	0,121	100	3264	0	13394
mid abutment padstone	13709	RC35/45	0,161	200	1142	0	3578
mid abutment walls	70258	RC20/25	0,121	100	2927	0	12014
end abutment foundations	45850	RC20/25	0,121	-	0	0	5548
mid abutment foundations	41126	RC20/25	0,121	-	0	0	4976
totals	**402.360**				**9.804**	**675**	**69.930**

Material specific carbon estimates have been based on the ICE database v3.0 [14]. Table 1 and Table 2 should be considered comparative rather than total, as a number of approximations have been made and sources of carbon have been (intentionally) omitted. One example of such an omission is the carbon associated with manufacture of the 3DCP elements in Denmark and transport by road to Ukraine. This would not usually be required, as the preference would be to manufacture as close to the site as possible. However, the conflict situation in the country prohibits this.

Similarly, the use of low-carbon concrete mix designs has not been included, due to the uncertainty over the supply chain in Ukraine. The comparison given could be reduced further by considering lower carbon constituent materials.

The embodied carbon rates for the concrete mix designs are given in the table but the rates for rebar and PT cables are 1.2kg/kg and 1.56kg/kg respectively. All values are for modules A1-A3 but the rebar and PT include the recommended allowance for recycled content.

This assessment suggests the potential for saving approximately 40% of embodied carbon with the new design, although it is noted that a significant component of this comes from the removal of the central pier and pier foundation (which would be possible with other bridge designs as well). The direct comparison of deck and beam embodied carbon shows a 23% reduction.

A note on the actual 3D printed concrete mix design, referred to as "D.fab" in the tables - D.fab is a set of specific admixtures developed by Cemex, in partnership with COBOD International, for printing with up to 10mm aggregate. This is a Eurocode 2 compliant mix design, which has a far lower cement content (because of the presence of aggregates) than would be typical for 3D printing mortar.

5 Differences with traditional RC construction

There are four primary differences that a designer must consider when working with 3DCP.

1. Layering: the printing method suggests a discontinuity between layers but inspection of printed cross-sections shows no apparent layering. Each concrete layer is extruded under pressure to force the layers to bond together.
2. Reinforcement: as described in section 3, reinforcement cannot be placed through the layers. Therefore the reinforcement detailing and print orientation must consider this constraint from an early stage. The perimeter permanent formwork approach allows conventional rebar cages to be used.
3. Casting times: if the printed formwork is to be part of the structural thickness, the bond between the printed surface and the infill concrete, poured 24 hrs after printing, must be addressed. Normally this kind of “day joint” would have rebar crossing.
4. Finish quality: printed layers, particularly with 10mm aggregate, are rough. An initial smoothing of the surface is possible with the printer head, followed by further smoothing by hand if necessary. However, fair faced concrete standards are not currently possible to achieve.

6 Structural details

The external post-tensioning cables follow a curve under the bridge deck. Saddles, where the cables are supported by the struts, shall be curved (see Figure 12) and sufficiently long to meet the bending radius requirements set out in the design guidance [15].

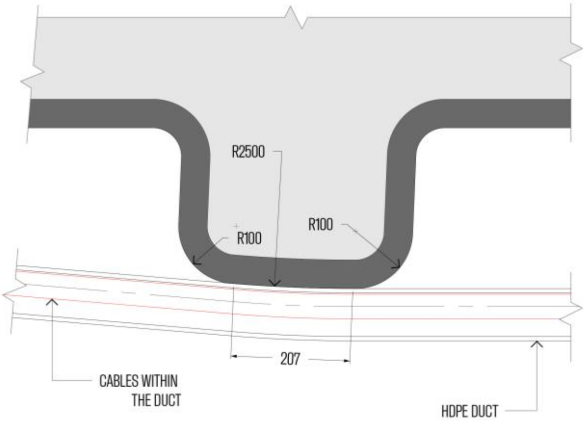

Figure 12: web – duct interface

The reinforcement shall ensure the full monolithic load transfer between the beams, the lattice slabs and the in-situ concrete. Figure 13 shows the reinforcement in elevation, where the bars can be laid across the print layer but not through the print layer.

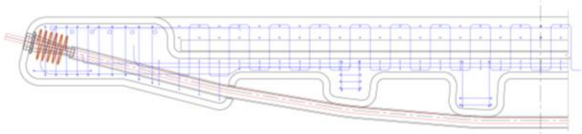

Figure 13: reinforcement – longitudinal section

The beam cross-section is shown in Figure 14, again sowing the bars across but not through the printed layers. The in-situ thickness of the concrete slab is 170mm, leaving the precast portion as 80mm. Adequate cover and robust detailing is required at all joints between prefabricated elements.

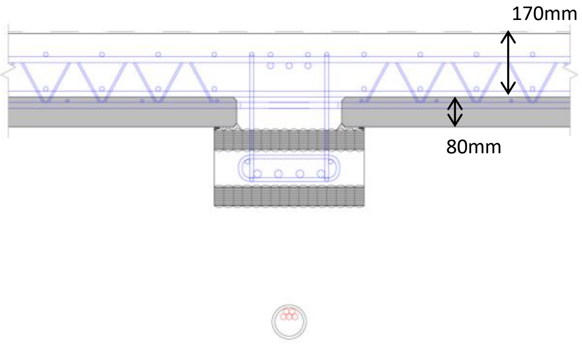

Figure 14: reinforcement – cross section

Torsion, in the permanent case is resisted by taking any rotation or moment in the slab reinforcement. However, in the temporary condition, the cross-section of the 3D printed part is sized and reinforced to accommodate the likely effects.

The end detail of each beam is yet to be finalised. However, the intention is to have an accessible pocket at each end to allow tendon inspection, re-stressing or replacement. The beams have been designed on the assumption of having a movement joint to isolate the thermal movement of the bridge at each end. The bearings and pockets have been sized to be replaceable. This approach is subject to detailed discussion with the local engineers and should adhere to typical construction practice.

7 Construction joint review

In addition to the 3D printed layer interface and the "day joint" between the printed and poured concrete, it is important to identify any other unusual joint locations, compared to accepted, standard practice. Figure 15 identifies the joint locations.

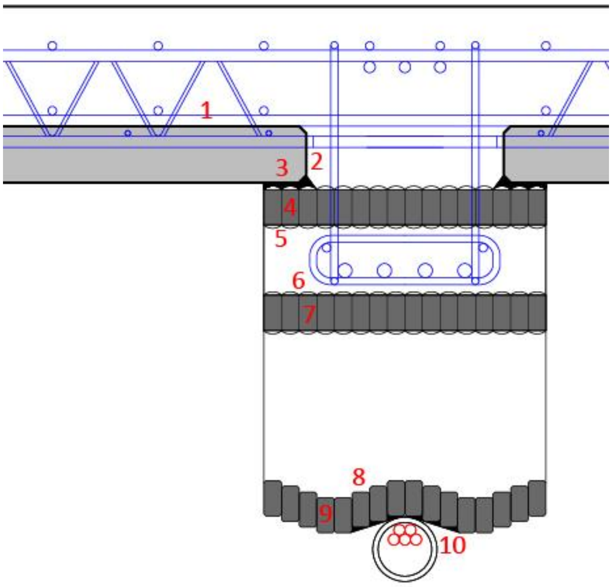

Figure 15: construction joints 1 to 10

Of the above 10 locations, it is only locations 6, 8 and 10 which require further description. Locations 6 and 8 are similar, where 3DCP interfaces with poured concrete, without reinforcement crossing. Ordinarily this would be avoided, however it is acceptable in this case as the joints are below the expected cross-section neutral axis in both the temporary and permanent conditions. In which case, they are part of the "tension zone" of the concrete, meaning they are not included in the ULS strength calculations.

Table 3: interface description

joint	description
1	standard interface, lattice slabs
2	standard interface, lattice slabs
3	standard interface, precast beams
4	3DCP layering, discussed in section 5
5	3DCP interface, with reinforcement
6	3DCP interface, without reinforcement
7	3DCP layering, discussed in section 5
8	3DCP interface, without reinforcement
9	3DCP layering, discussed in section 5
10	3DCP to duct interface

Location 10 is where the duct touches the 3D printed concrete. This surface will be treated with a friction agent, such as nylon, to improve the relative sliding between the two components.

Rough surfaces are specified at concrete interfaces, as they allow higher forces to be transferred, implying better durability.

8 Future developments

The original conception of the minimass beam included webs made entirely from printed, unreinforced concrete, where the width of the web is less than the overall width of the beam. Neither of those two aspects are included in this design but both are feasible future developments. Unreinforced webs would give even greater geometrical freedom, reduce embodied carbon further and avoid the risk of steel corrosion from chloride ingress. However, they would require a reliably constant axial compression from the cables. In the temporary case, these unreinforced webs might be supported by an external jig which could be removed and reused.

The width of the web is related to the print path and the task of filling the printed formwork. Narrower webs would reduce the weight and the embodied carbon but there is work to be done to develop this approach.

9 Conclusions

The need for innovative, affordable and sustainable re-construction in Ukraine is clear. Minimass offers a new approach which uses less material and less labour, by working with optimised geometry combined with digital manufacturing processes.

At the time of writing, this bridge design has not been built but the approach described highlights the key design and construction challenges which have been or will need to be overcome.

Specific material testing will be carried out in Ukraine and further research and development will take place for these techniques.

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