From Dream to Reality

Building Leonardo da Vinci's Bridge in Norway

By Richard G. Weingardt, P.E.

The first and only bridge structure ever built using the plans of one of the world's greatest Renaissance men Leonardo da Vinci (1452-1519) – painter, sculptor, architect, engineer and scientist – was brought into being in October of 2001. Its gala unveiling was presided over by Norway's Queen Sonja and attended by a large enthusiastic crowd braving stormy weather.

A special public arts project that used exposed structure as its medium, the da Vinci Bridge – located just south of Oslo, Norway, at Nygardskrysset in the small municipality of As – is recognized as one of Europe's most unque and spectacular bridges. Elegantly spanning E18, the main four-lane motorway between Oslo and Stockholm, Sweden, the sleek-looking, multi-arched timber structure cannot be passed by (or under) without turning heads and eliciting notes of amazement.

Bjorn Lund, structural engineer on the project for Reinertsen Engineering (consulting engineers), said, "Apart from some minor durability [weathering] concerns, one may conclude that the Leonardo da Vinci Bridge was a highly successful project. It has attracted considerable attention and many positive comments. And although it is neither an engineer's bridge nor the most efficient way of bridging a highway, it serves its function. It provides road users with a beautiful sight, the municipality with a sculpture, and pedestrians and bikers passing over the bridge with a unique experience. Plus, it is sure to lead to increased public interest for bridges in general."

How did it all come about – this building of a modern-day bridge based on forgotten, 500-plus-year-old concepts and sketches?

First we need to go back to 1502, when the great da Vinci initially revealed his bold plans for a sweeping column-free structure to span the wide Bosporus River. His proposal was in response to Sultan Bajazet II of the Ottoman Empire, who wanted to replace a floating timber pontoon bridge crossing the Golden Horn in Constantinople harbor with a more permanent structure. Da Vinci's daring structural design, a massive, single span stone bridge, consisted of three parallel arches – one central vertical arch carrying the vertical loads and two inclined arches, one on each side of the main arch.

The vertical central arch, with a height to span ratio of 1:6 and a "pressed-bow" profile, closely followed the bridge's thrust line. The bridge's narrow roadway width produced a very slender structure with regard to lateral loading, so, in order to achieve lateral stability, the inclined side arches were flared out at both ends of the bridge. This crafty configuration, additionally, helped spread out the vertical loads on the soils at the bridge's abutments.

Da Vinci's Golden Horn bridge would have been the world's largest single-span stone structure in history – having a total length of 360 meters, a clear span of 240 meters and a vertical clearance of 40 meters. However, overwhelmed by the structure's huge scale and daring design, the sultan developed doubts about its practicality and the great bridge was never built – and da Vinci's sketches and notes were archived for half a millennium.

In 1995, one of Norway's most celebrated young artists Vebjørn Sand saw a model, along with sketches, of da Vinci's centuries-old bridge concept at an exhibition in Stockholm, and he was fascinated, to say the least. So captivated by the bridge's structural design beauty and boldness, he became obsessed with building a version of the bridge in Norway, *not* in stone as da Vinci proposed, but in wood using glue-laminated (glulam) timber consisting of native Norwegian pine. Norway's version of da Vinci's bridge, held Sand, needed to be "an interpretation expressed in wood."

To move the project along, a special design and management task force was organized. It included, in addition to Sand as the artist and ringleader, local architects and structural engineers, a prominent Norwegian glulam manufacturer (Moelven Limtre) and local Public Roads Administration officials. Cru-

Massive computer programmed and guided grinding-cutting machine shaping the main glulam arch to the specified structural shape, size and form.

Main timber arch partially ground to its intended cross-sectional shape. Epoxy and laminated seams and embedded connection plate are in the foreground.

View showing the slender steel pipe pillars (columns) that support the pedestrian pathway from the arched timber structure, which spans the motorway, to the terminus of the deck at ground level. Also, evident is the detailing of a splice connection in the main vertical arch.

cial initial issues effectively addressed were locating an appropriate site and determining the proper bridge type and size, and then securing the necessary funding.

Once it was decided that Norway's da Vinci would be a footbridge over the busy E18 motorway 20 kilometers south of Oslo, structural and architectural designs were quickly implemented to translate da Vinci's concept into an actual structural form – and to determine optimum member sizes and shapes. All in accordance with the visual expression Sand wanted to achieve.

Said Sand, "The shape of the [Norwegian] footbridge follows the lines of da Vinci's sketches, but in a more pronounced way. The use of glulam timber required a lighter and more minimalistic structure – in reality, a new structure. Still the new modern glulam timber structure possesses all the main structural elements of the old stone bridge – the bridge way, with its sag at both sides, vaults over the arches in an elegant way. The main thrust arch carries the vertical loading and the inclined arches provide lateral stability just as in the original stone bridge concept."

Computer-generated architectural renderings and a to-scale model were produced early on to inform the public of the project, and to aid in money raising efforts. Funding for the project came from various sources – government, industry and private contributions. Overall, planning, fund-raising, design and construction took nearly five years, from 1997 until 2001.

As reported by Tormod Dyken with the Norwegian Public Roads Administration: "The static system of the bridge consists of three non-hinged glulam timber arches with a rounded, triangular cross section decreasing in size from the abutments to the apex. At the abutments, there are fixed ends provided by bonded-in steel rods. The center arch is made up of four segments, the other two of three segments, which are rigidly connected by slotted-in steel plates and dowels. The complex surface of the arches was specified by co-ordinates of a 150 by 150 mm surface mesh, and from these co-ordinates, the wood was shaped by a computer aided grinding machine.

"The bridge deck is supported by the main arch in the middle, following the convex shape of the arches. At both sides, the deck has a sag as indicated by da Vinci's sketch and the necessary support is provided by slender steel pillars. The use of stress laminated glulam beams (decking) for the bridge deck makes it possible to follow the smooth lines of the concept. The beams are pre-curved and clamped together by pre-stressed, high-strength steel bars forming a continuous ribbon-like slab. The deck is provided with a watertight membrane as a wearing course.

"The bridge is very exposed to weathering as it is provided by very little protection by structural means. Metal cladding, plastic coating, wooden paneling, etc., were all turned down for aesthetic reasons, leaving chemical protection as the only option for obtaining a reasonable operating life. Among the chemical alternates, creosote was ruled out for optical reasons (too dark) and CCA-treatment was ruled out for environmental reasons, ending up with a number of environmentally friendly systems in order to compensate for less effect and lack of long term experience."

The main applied systems used were:

- Each single lamella in the arches was pressure treated with Scanimp, a heavy metal-free agent of class AB, which is not recommended for soil contact.
- The glued, grinded and finished arch elements were pressure treated with Ultrawood, a water-based wax emulsion to produce a water-repellent surface.
- In order to further prevent ingress of water, the finished structure was also treated with two coats of oil stain with some pigmentation. (The treatment must be repeated every few years.)
- To provide the areas of the glulam arches, which are particularly exposed to moisture, with additional protection, boron bars were inserted into pre-drilled holes near the abutments. These bars remain inactive as long as the timber stays dry, but with ingress of moisture, the boron gradually dissolves to prevent rot. The boron bars must be regularly inspected and replaced as required.

The Norwegian government's design rules for bridges require a design service life of 100 years for all bridges – including timber bridges. With the above treatment, this requirement cannot be fulfilled. The da Vinci service life was estimated to be about 40 years without any reconstruction works. So, an exception from the design rules was given for the bridge on this point because of artistic and aesthetic grounds.

Deflections, Vibrations & Wind Dynamics

Because structural members were so small in cross-section to give the bridge its very light appearance, deflections, vibrations and wind forces were major design concerns.

According to Lund, who has a master's degree in structural engineering from the University of Washington: "Vibration criteria were important during early stages of the design process, that is vibration level caused by people crossing the bridge. Norwegian regulations states that the reference vertical acceleration shall be smaller than 0.25 times 10 (to the power of 0.7782 times log f) times m/s2, where f is the bridge's first vertical natural frequency (Hz).

"For a bridge with a first natural frequency of say 2.5 Hz, the acceleration shall be smaller than 0.51 m/s2; for 3.5 Hz, the acceleration shall be smaller than 0.66 m/s2. This requirement had influence on span lengths etc."

Regarding wind dynamics, Lund said, "The bridge was analyzed for wind buffeting, that is, dynamic amplification in along wind direction. The calculations indicated no significant buffeting response. I don't think we made any formal calculations on vortex shedding for this bridge, from my experience with vortex shedding on pipelines in the North Sea and bridge design in general, vortex is mainly a problem with regular cross section in uniform streams (wind or current induced). This can be the case for bridge hangers or for long suspended-span bridges, however the Leonardo bridge walkway shape and bridge cross section do not indicate such problems. No disturbing wind dynamic response has been reported to me from the site."

The maximum span of the bridge deck/walkway, made up of glulam beams and prestressed by transversal steel bars, is about 11.9 meters. The people-induced vertical vibrations were determined to be well below the government's design requirements – maximum calculated deflection, under full load, was approximately 20 mm vertically and 35mm laterally.

Lund reported, "No annoying vibrations have been reported from the bridge. During the opening ceremony the bridge was completely covered by people, so I guess maximum live load was present at the opening day of the bridge."

Computations

In completing its structural computation and stress analysis, Reinertsen mostly relied on SOLVIA and STADD III computer programs, plus special hand calculations for certain critical elements of the design.

In the final analysis, said Lund, "The bridge cross sections were not highly utilized regarding stress control."

Glulam Quantities & Stresses

The volume of glulam timber used on project amounted to 90 cubic meters for its arches, and 120 cubic meters for its stress-laminated bridge deck.

The glulam quality specified was GL 36c, with a nominal bending stress strength of 36 MPa (N/mm2), along fibre axial compression strength 29 MPa. The required modulus of elasticity was 14700 MPa.

Glulam Fabrication

The three arches, structurally interconnected at their apex, have quite large cross sections, up to 1200 mm wide and 1800 mm deep at the bottom. To be able to manufacture glulam structures with such huge dimensions, Moelven Limtre utilized several innovative procedures including a unique two-step gluing process.

The first step was to produce curved beams of 120 mm pressure impregnated Scots pine up to a depth of 1800 mm. The next step was then to glue these large sections together to the final width of the construction (maximum 1200 mm). In this second gluing operation a special gap-filling phenol-resorcinol adhesive Dynosol S-204, which is approved for glue line thickness up to 2 mm, was used.

After the gluing operation, the next challenge was to form the glulam sections to the desired shape according to the artist's renderings and engineering/architectural drawings. To this end the arches were machined in a three-dimensional way with a computerized cutter/grinder.

After the elements had been machined into their final shape, they were pressure impregnated with a wax emulsion to a depth of 5-10 mm to create a water-repellent surface. Finally, to further preserve the wood, three coats of lacquer were applied to the dried surface. The treatments used to protect the wood are colorless, so the bridge reveals the natural beauty of the native Norwegian wood.

Foundations

Because of the rather poor clay soil conditions at the site, the bridge had to be founded on concrete piles solidly founded into bedrock. Since the rock profile was moderately inclined, with the lowest point near bridge mid span, the piles were of varying depths and lengths. They were connected together at their tops with a concrete pier cap.

A total of eight different concrete foundation types were used. The ones below the steel columns were the smallest while those supporting the arches were significantly larger. Lund stated, "We used 270 mm x 270 mm concrete driven piles, maximum pile length of approximately 15 m supporting the main foundations. At the bigger ones, a total of 16 concrete driven piles were used. For one foundation, we replaced the concrete driven piles with four concrete in-situ made piles of diameter 1200 mm."

Erection & Construction

The arches came in several pieces and were connected at the site, with minimum traffic obstruction. The central arch was erected in one day without delaying traffic at all.

As outlined by Lund, "The basic principle used for connecting the arch pieces into complete arches was:

- The arch pieces were made with slices at the ends, steel plates 8 mm in size were fitted into the slices.
- The steel plates were then connected to the laminated wood by putting 12 mm diameter steel dowels through the steel plates and the laminated wood. So it's true that moment resistive connections were used at arch joints.
- For the central main arch, the moment rigidity at base was made by in-glued bars using high strength epoxy."

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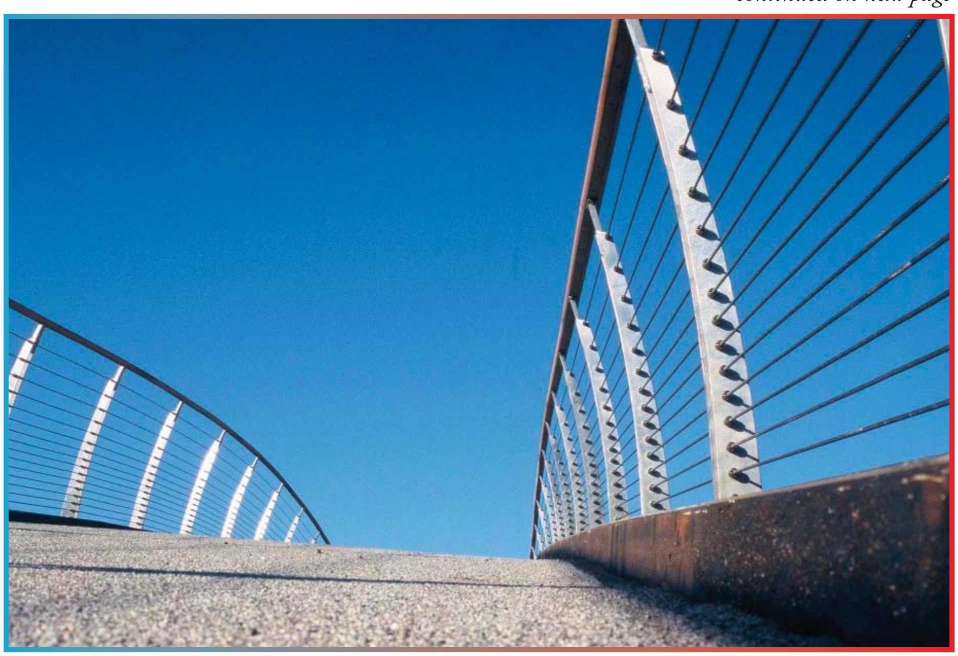

Stainless steel handrails and cables against the Norwegian sky

Final Product

Nygardskrysset's stunning Leonardo da Vinci timber pedestrian bridge ended up being 109 meters in length with a main span of 40 meters and a maximum height, over the motorway, of six meters. It's final cost was 1.5 million Euro, with one third of the cost – 0.5 million Euro – being for the glulam timber portion of the project.

The legendary Princeton University structural engineering professor David Billington, who coined the phrase "structural art," stated: "The first fundamental idea of 'structure as art' is the discipline of efficiency, a desire for minimum material, resulting in less weight, less cost and less visual mass." Norway's da Vinci, which has become a striking landmark in the local community, undoubtedly attempts to fulfill Billington's criteria.

Pedestrians exiting at the west end, after crossing over the bridge.

In the future, the project's instigator and mastermind, artist Vebjorn Sand, is optimistic about building a da Vinci bridge on every continent, utilizing local materials and unique methods of construction. He currently has Leonardo Project plans underway in China, Turkey and the United States. On his U.S. project – near Odessa, Texas – exposed structural steel and Permian Basin limestone are the dominant materials.▪

All photos courtesy of Age Holmestad and Jostein Elde with Moelven

Richard G. Weingardt, PE, is CEO of Richard Weingardt Consultants, Inc. in Denver, CO. He is the author of eight books. His latest Engineering Legends, published by ASCE Press, features numerous great American structural engineers. Weingardt was the 1995-96 national president of ACEC. ***rweingardt@aol.com***

Project Credits

Owner: Norwegian Public Roads Administration, Eastern Region

Design group:

- Vebjorn Sand – artist, mastermind and ringleader
- Reinertsen Engineering ANS – consulting engineers
- Selberg Arkitektkontor AS – architects
- Moelven Limtre AS and Norwegian Public Works Administration, Road Directorate – advisors
- Norwegian Public Roads Administration, Akershus – project managers

Contractors:

- Norwegian Public Roads Administration, Ankershus
- Moelven Limtre AS (subcontractor for the production and erection of the timber structure)▪