IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Conceptual Design Of Chenab Bridge

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Abstract: The Chenab Bridge, an engineering marvel spanning the Chenab River in the Reasi district of Jammu and Kashmir, India, stands as the world's highest railway bridge and a symbol of infrastructural innovation. Designed as a steel arch bridge, it rises approximately 359 meters above the riverbed, surpassing even the height of the Eiffel Tower. Engineered to withstand extreme wind speeds, seismic activity, and challenging Himalayan topography, the bridge incorporates state-of-the-art materials and construction techniques, including weathering steel for longevity and a blast-resistant design for enhanced security. The structure exemplifies a harmonious integration of aesthetic form and structural function, with its arch geometry ensuring optimal load distribution across deep gorges. Beyond its technical brilliance, the Chenab Bridge plays a critical strategic role, connecting remote regions and enhancing socio-economic integration in one of India's most geopolitically sensitive zones. Its completion represents a landmark achievement in high-altitude bridge engineering and resilient infrastructure development. The Chenab Bridge's conceptual design and structural design principles are described in this study. The major goal is to describe the unique bridge concept in difficult terrain and to provide an overview of the design solutions employed in one of the world's tallest steel arch railway bridges. The construction of a new railway line in India has been taken on by Indian Railways as a mega-project in the state of Jammu and Kashmir. The project includes a large number of tunnels and bridges which are to be implemented in highly rugged and mountainous terrain. The alignment crosses a deep gorge of the Chenab River which necessitates construction of a long span railway bridge. The deck height is 359m and bridge length is 1315m. Indian railways constructing the iconic arch bridge on river Chenab as a part of the USBRL project to connect Kashmir valley to the rest of nation. Arch bridge completely made of steel. Foundations and the approach viaduct piers are made of concrete. This report describes the design and engineering of the bridge. The bridge has numerous design challenges such as erection of the steel arch by cable crane, the bridge's huge dimensions, and the special design requirements- redundancy of the arch, the earthquake load and blast load effect. The challenges in the design and erection of the bridge is described in this paper.

Index Terms **–** Conceptual Design Approach, Geotechnical Considerations, Structural Design Aspects.

I. INTRODUCTION

To provide an alternative and reliable transportation system to Jammu and Kashmir, the Government of India planned a 272 km long Rail way line from Udhampur to Baramulla joining the Kashmir valley with the Indian Railways network called the Udhampur -Srinagar -Baramulla Rail Link project (USBRL). The project has been most challenging works undertaken since 1947 by Indian railway. In view of the importance of the USBRL project in providing seamless and hassle-free connectivity, the project was declared a "National Project" in 2002.The alignment of USBRL involves the construction of large number of tunnels and bridges in highly rugged and mountainous terrain with the most difficult and complex Himalayan geology. The USBRL Rail Link project include the iconic Chenab Bridge project which is being constructed in the reasi district of the Union territory of Jammu and Kashmir. The bridge is about 111 km by road from Jammu on the ongoing Karta-Banihal section. The bridge across the river Chenab having a central span of 467 m is being built at a height of 359 m from the bed level. For comparison, the height of the Qutab Minar monument in New Delhi, India is 72 m and of the Eiffel Tower in Paris, France, is 324 m. It is the highest railway bridge in the world ever constructed. For the construction of the Arch portion of the bridge over the river, a novel method of construction using the crossbar cable crane was designed and commissioned. The cross bars having a capacity of 20MT (metric tonnes) each and 36 MT in tandem run on 54mm cables laid across the river valley and are connected through a 127m high pylon (tower) on kauri side and 105m on the Bakkal side of the river The Chenab Bridge will usher in a fresh era in Jammu and Kashmir thanks to increased employment opportunities for the young population, improved infrastructure by virtue of the construction of access roads, and better facilities for students to travel to other parts of the country for educational purpose It will also boost the tourist industry, connectivity to distant areas to the mainstream of the country and overall economic development of the state Remotely located villagers at the kauri and Bakkal ends who until now have no vehicular means to travel to the Reasi district and other Places have started enjoying the construction of black-topped approach roads in the region. In fact, a window to a world of opportunities has opened up to the local population of the region.

II. UNIQUE FEATURES OF CHENAB BRIDGE

- Bridge designed to withstand maximum wind speed of up to 226 km/h (74m/s).
- Bridge designed for blast in consultation with DRDO (Defence Research and Development Organization) for the first time in India.
- Bridge designed to resist earthquake forces of highest intensity zone-V in India.
- First time on Indian Railways, the phased array ultrasonic testing machine used for testing of welds.
- First time on Indian Railways, National Accreditation Board for testing and calibration. Laboratories (NABL) accredited lab established at site for weld testing.
- Provision of long weld rail (LWR) over the bridges and resulting force calculation as per UIC-774-3R (code for Track Rail Interaction) guidelines.
- Design life of 120years.
- Incremental launching of deck structure on combined circular and transition curves was done for the first time in the Indian Railway.
- World’s largest capacity crossbar cable crane used for the erection of piers, trestles and arch segments.
- Extensive wind tunnel testing – Topographic model study and Aero-elastic model study for the first time in India.
- Installation of the double corrosion-protected bar and cable anchors for the first time in India in Indian Railway.
- 10.9 grade M36 HSFG Bolts with cement coating.
- Blast Resistant Design.

III. SPECIAL CONSIDERATIONS IN DESIGN

3.1 Geographical Location:(In The Vicinity Of Snow-Clad Himalayas Mountains)

- The Bridge is designed for temperature for -10^{C} to 40^{C}.
- The adaptation of special structural steel e.g., E10C, E410C+Z15, E410C+Z25, E410C+Z35.
- Seismically highly active area-zone V- site specific response spectrum, Dynamic Analysis of structure and Ductile Detailing.

3.2 Geological Condition (Unstable Slopes And Erratic Geology)

- Very detailed geotechnical and geological investigation.
- Extensive slope stability analyses.

3.3 High Wind Speeds

- Stopping of trains if wind speeds exceed 90 km/h (25m/s).
- Design based on wind tunnel tests.

3.4 Sensitive Border Area

- Even after the removal of one pier, the bridge will not collapse under self-weight.
- Redundancy: Even after removal of one critical member of the arch, the bridge will still be able to carry the traffic at a restricted speed.
- Even after removal of one critical member of a pier and arch, the bridge will still be able to carry the traffic at a restricted speed.

IV. GEOLOGY OF THE AERA

The Chenab Bridge is situated in the most difficult portion of the Jammu-Udhampur-Srinagar- Baramulla rail route, which is characterized by young Himalayan rock. Broken rock with dolomitic limestone and firestone lentils with a silicate concentration make up the topography. Rock formation exposed to between Jammu and Quazi Gund are crossed by three major thrusts besides a number of local thrusts, shear zones and faults. There are rocks of class 3 to 5 with strength of 60 to 100 MPa and a volume weight of 2.7 t/m3. The RMR (rock mass rating) is aMeasure of the amount of rock in a certain area. The State of Jammu and Kashmir is one of the largest Union Territories of the Indian Union and is situated at the base of the Himalayas. It lies between 32^{o} 15' to 37^{o} 05' latitude north and 72^{o} 35' to 80^{o} 20' longitude east. It lies between 32^{o}15'to 37^{o} 05' latitude north and 72^{o} 35' to 80^{o} 20' longitude east. Jammu and Kashmir are home to several valleys such as the Kashmir Valley, Tawi Valley, Chenab Valley, Poonch Valley, Sind Valley and Lidder Valley. The main Kashmir valley is 100 km wide and 15,520 km^{2} in area. The Himalayas divide the Kashmir valley from Ladakh while the Pir Panjal range, which encloses the valley from the west and the south, separates it from the Great Plains of northern India. Along the Northeastern flank of the Valley runs the main range of the Himalayas. This densely settled and beautiful valley has an average height of 1,850 m above sea level, but the surrounding Pir Panjal range has an average elevation of 5,000m.The railway line passes through the Himalayan Mountains i.e., outer Himalaya (sub-Himalaya), lesser Himalaya and great Himalaya, see Figures 1 and 2. The Chenab Bridge is located at Chainage km 51.800 between Bakkal village (left bank) and Kauri village Geology along the Chenab Bridge from the left to right bank consists of three formations, namely Sirban limestone group, Jangalgali/Kheri formation and Subathu formation. The slope stabilization measures for the Chenab Bridge are based on geological logging and using DIPS software for kinematic analysis and SWEDGE software for wedge failure analysis. For the first time in India Railways, 33.5m long double corrosion-protected pre-stressed Dywidag bars anchors were installed for slope stabilization work on the right bank. The major rock types encountered and exposed are Jointed dolomite, Brecciated dolomite, and Cherty Dolomite with different degrees of weathering and fracturing. Quartzite with a shale band was also observed at the Kauri end. The dolomite encountered is mainly dark grey to grey in colour. It is mostly weathered on the surface. In some places, it occurs as prominent warping at different slopes. The dolomite falls under Sirban series of dolomite. It is fresh, hard and competent. The rock units have undergone tectonic movement and local folding/warping was noticed. Rock unit generally strikes NW-SE and dip at 30° to 50° towards NE direction. However, rock units on both sides, i.e., left as well as right banks, are locally folded in the form of warping. The entire area comprises hilly terrain traversed by numerous small and large nallas. Terrace farming or step-wise farming is done on hill slopes. The area is highly undulating and with rugged topography, It is characterized by strike ridges, dip slopes with scarps and drainage patterns controlled by bedding joints and other joint planes.

Fig 1: Alignment of the railway line

4.1 Topography On Bakkal Side

The area on the left bank has a maximum elevation of ±845m near Bakkal village. In general, hill slope areas are very steep with slope angles varying between 50^{o} – 60^{o}.The Bakkal end hill slope is covered with debris/soil, the thickness of which varies from 1 to 3 m but in some places rock exposures are encountered. The slope is made up of highly jointed to blocky dolomite, brecciated dolomite/brecciated quartzite.

4.2 Topography On Kauri Side

The area on the left bank has a maximum elevation ±850m near kauri village. The slopes are very steep with slope angles varying between 50^{o} – 75^{o}.The Kauri end hill slope is covered with debris/soil and vegetation. Their thickness varies from 1 m to 3.5 m but in some places rock exposures are encountered. The slope is made up of highly jointed to blocky dolomite, brecciated dolomite/brecciated.

V. ESTABLISMENT AND LOGESTICS AT SITE

Managing major construction projects like the Chenab Bridge requires an integrated approach to logistics with respect to the mobilization and establishment of workshops for the execution of work at site. Sophisticated workshops were developed at the Bakkal and Kauri sides for carrying out the fabrication of deck segments, arch segments and pier segments. These workshops were equipped with sophisticated CNC Cutting machine, CNC Drilling machine and welding equipment. Internal approach roads 3 – 4 km long were constructed for the mobilization of material, tools, and equipment which was one of the biggest challenges due to the hilly terrain, narrow and sharp curves, and with land sliding-prone areas though out the stretch. The plates and the outsourced segments for trestles and the arch were planned to be stacked at the central yard of Reasi, 35 km away from the site, as the 12m trailers on which these segments were being transported could not travel directly to the site location due to turns/sharp curves and with insufficient width for the movement of such trailers. The material from the central yard was then transported to the site using 9,8m trailers – all material was supplied to the site by these trailers only.

VI. CHALLENGES FACED DURING LOGISTICS

There were many other challenges encountered and some of them are as follows:

6.1 Land Slides

Logistics of the material, workforce and equipment through these hilly terrain roads during the heavy rains was very difficult as there were always slides of unstable rocks from the mountains. The vehicles were often delayed for many days during clearance of the road.

6.2 Remote Location Of The Site

Due to the remote location of the site and the bad condition of roads, logistics of material, workforce and equipment could not be carried out at night which impacted the pace of the project. A fleet of trailers was escorted from the Reasi yard to the site location. Supervision of road conditions was monitored prior to the actual movement of trailers.

6.3 Widening Of Roads

The transportation of the segments on the other side of Chenab valley was obstructed because there was insufficient width for the transportation of the segments on the Bailey bridge constructed by the BRO (Border Roads Organization). The site management took the decision to change the alignment of the road by constructing a side-by- road to the existing bridge for the transportation of segments.

VII. CHALLENGES FACED DURING THE ERECTION

There are many challenges faced during the erection some of them are follows

7.1 Dependency On Cable Crane

The cable crane was a critical construction machine and the only source for erection activity in this project due to its location and height. However, cable crane operations could be affected by heavy rains, gale-force winds, thunderstorms, and lightning which affected the arch erection productivity. Therefore, detailed planning and time-bound activity were of utmost importance.

7.2 Alignment Of Erected Segments

Alignment of arch segments was very important for controlling the geometry of the arch. This involved meticulous and regular surveys during the erection of arch segments. Temperature and wind monitoring were crucial during the erection and survey. Surveys were done early in the morning to avoid temperature variation. Arch erection was stopped if wind speed exceeded 15m/s. Temperature played a crucial role during the erection.

7.3 Trial Assembly Of Arch Segments

Before the arch erection, the geometry at ground level was checked so that any modification or alteration could be done on the ground before erection. It could have been extremely difficult and risky to rectify errors at such precarious heights after erection

7.4 Long Wind Bracings Erection

Transportation and lifting of wind bracings to the erection location was a challenging task due to their length and weight the length is around 40m. The uneven mountainous terrain made transportation of the wind bracings extremely difficult. Before the erection of wind bracings, platforms were provided at the location to ease the erection with proper safety measures. Pre- assembly was done with the required degree of inclination to erect as per the required geometry. Accordingly, arrangements were being made for the lifting of wind bracings. After erection, in-situ welding was done at the required locations which was a difficult activity under windy conditions.

7.5 Torquing Of High-Strength Friction Grip (HSFG) Bolts

Torquing plays a vital role in the erection of the arch. Shifting the equipment for torquing at such height and location is challenging and consumes time. Working at height is very risky and needs specialized teams and platforms with safety measures in place. It is impossible to retrieve any HSFG bolt if it, unfortunately, slips and falls into the river from such height

VIII. DESIGN OF THE BRIDGE

The arranging of this endeavor has been accomplished through WSP team (Finland) and sketch of curve is cultivated by utilizing sub aide Leonhardt. Indian Rail line Norms (IRS Principles), IRC, IS have been utilized while planning the bridge.BS:5400 is being utilized as the straightforward fundamental for the organization and improvement of the extension. The design speed of the rail line used to be set to be 100 km/h and the graph ways of life must be one hundred twenty years. Weariness assessment will be accomplished according to BS:5400 section10. The most sophisticated TEKLA software used for structural detailing. The profound Chenab Stream valley under the extension is inclined to high wind pressure taking a chance with the strength of the scaffold. Notwithstanding all traditional railroad connect loads this scaffold needs to support uncommon impact loads determined by Indian rail route. Norway based power innovation research center led a few air stream tests to comprehend the impact of wind speed, static power coefficients and blast slamming. Wind burdens will be determined utilizing actual geographical models of the site and tests in an air stream research facility. The test aftereffects of the extension are utilized to extricate identical static breeze loads, which are utilized in the last underlying examination. Wind loads will be derived using typical topographic models of the site and tests in a wind tunnel laboratory. The service wind load compares to a greatest breeze pressing factor of 1500 Pa. The breeze load is overseeing the curve plan. The extension is intended to oppose wind velocities of up to 260km/h. The seismic idea of the venture zone was additionally considered during its plan. The limit state theory of configuration has been chosen to be followed according to BS codes. Arrangement of since quite a while ago long welded rail (LWR) over the extension and coming about power computation according to UIC774-3R rules. Distortion restricts according to comfort models of UIC 776-2R and UIC 776-3R rules. The utilization of curve is only one way that designers can uphold the dead burden and live heap of the extension. The heaviness of dead burden and live burden consolidated has the impact of a descending power, the gravitational power. In a curve connect the descending powers are generally dispersed down to the projections, the two base backings of a curve that are safely secured in the ground. Since the extension is very still, the projections subsequently have an equivalent and inverse power to the descending powers. The extension will incorporate 17 ranges, just as 469m primary curve length across the Chenab Waterway, and viaducts on one or the other side. The primary range of the scaffold will incorporate two 36m long methodology ranges. It will work as a two ribbed curve with steel brackets made of cement filled fixed steel boxes. The design will be upheld by two 130 m long, 100m high arches on one or the flip side through links. The arch and arch piers of the Chenab Scaffold will be produced using enormous steel supports. To give least wind obstruction, the harmony of supports and the diagonals are altered to become fixed steel boxes. Any remaining individuals including optional individuals were kept round, which extraordinarily improves on the association subtleties. The harmony individuals will be loaded up with concrete to help with controlling breeze prompted powers on the scaffold by improving damping proportion and solidness. The substantial fill likewise improves the general strength. In the curve part of the superstructure is upheld on steel wharfs with a tallness of up to 120m. Extension joints are given toward the end projections and at wharf S70 that different the principle curve ranges from the methodology connect. At this area there is additionally an adjustment of the deck stature. The mark of longitudinal fixity of the curve connect deck is at curve focus, where the powers are sent most proficiently and relocations at either end are negligible. The superstructure is a plate brace with a shut deck, where rails are associated. The shut deck keeps the water and gives generally Dry climate beneath the deck. Wind noses of the deck is given in the primary curve divide. Launching of curved viaduct portion done for first time on Indian Railways using End Launching method. NABL (National Accreditation Board for Laboratories) accredited lab established at site for weld testing. Steel was picked to develop the scaffold as it will be more prudent and readier to oppose temperatures of - 20^{o} C and wind rates of above 200km/h. The Jammu and Kashmir area observer to visit fear monger assaults. To upgrade the wellbeing and security the extension will be made of 63 mm thick uncommon impact evidence steel. The substantial mainstays of the scaffold are intended to withstand blasts. It is normal that the construction will actually want to withstand quakes of greatness eight on Richter scale and up to 40 kg of dynamite impact. Bridge designed to bear earthquake forces of highest intensity zone-V in India. A ring of elevated security will be given to protect the extension. A web-based checking and cautioning framework will be introduced on the scaffold to ensure the travelers and train in basic conditions. Pathways and cycle trails will be given adjoining it. The scaffold will be painted with extraordinary consumption safe paint which goes on for a very long time.

IX. BRIDGE CONSTRUCTION

The scaffold's development guideline involves a huge extension curve with access viaducts at each side. The enormous curve planned as a 2-overlay ribbed curve including steel supports with platform supports delivered on the spot. 5 scaffold columns for the entrance viaducts are made of steel and 13 of cement. The steel constructions of the scaffold will be fabricated in workshops worked in the mountains. Four workshops have been underlying the mountains. Workshops and paint shops worked close to them are situated on the two sides of the valley. All steel materials, with the exception of the little moved profiles, are conveyed to mountains as steel sheets. All power created at site and water provided from additional away in mountains. The extension will comprise of 25000 tons of steel structures, the principle bit of which will be utilized for the curve connect area. Initial a link crane will be worked over the valley for building the steel structures. The link crane will move between arch pinnacles based on the two sides of the valley. The crane can convey a greatest measure of 40 tons of steel parts. Derrick crane introduced, which is equipped for lifting around 100 tons. For the first time continuous welded plate girder used on railway bridge.

9.1 Foundation

To set up the establishments for the extension in the troublesome territory, safe uncovering at the two sides of the valley is being ready for a terrific scope, penetrating for establishment. The tallest wharf is 137.7m tall, a particularly tall design is required gigantic establishment of 150m*36.5m.

9.2 Slope Stabilization

The side slant of the valley differs from 43^{o} to 77^{o}. The incline adjustment measures are finished by Indian Organization of Science. After uncovering of rock bolt of design length of 4m, 8.5m and 11.5m are introduced. Permeable lines are introduced to forestall the hydrostatic pressing factor. Guniting with steel support is given to reinforce and balance out the slant.

9.3 Deck And Arch Construction

The steel structures of the bridge will be manufactured in workshops built in the mountains. The workshops have been moved to the building site, because there is no proper road network in the challenging terrain. The longest building parts that can be delivered to the site are 12 meters in length. Therefore, four workshops have been built in the mountains. Workshops and paint shops built next to them are located on both sides of the valley. All steel materials, except for the smallest rolled profiles, are delivered to the mountains as steel boards. The insufficient infrastructure of the area causes additional problems. There is no electricity and the water of the river is not suitable for manufacturing concrete. All electricity must be produced at the site and the water is delivered from further away in the mountains. The job is also challenging, because the track has curvature in the approach bridge. In this section, the construction stage bearings have been designed in such a way that it is possible to launch the steel deck in the curvature portion as well. The bridge will consist of about 25000 tonnes of steel structures, the main portion of which will be used for the arch bridge section. First, a cable crane will be built over the valley for constructing the steel structures. The cable crane will move between pylon towers built on both sides of the valley. The crane can deliver a maximum amount of 40 tonnes of steel parts. For example, the over 100 meters long steel columns with bolted couplings will be constructed using this technique. When the long steel columns are ready, the steel deck will be Pushed on top of the columns. After this, a derrick crane, which is capable of lifting about 100 tonnes, will be placed on top of the deck. Deck erection will proceed simultaneously with the erection of the arch. Both the arch and the deck cantilever freely by up to 48 meters. When the next arch pier location is reached, temporary cables will be installed to support the arch, and the new arch pier will be constructed on the free end. The superstructure can then be supported by the arch pier and so forth until the last arch pier is reached. The very last span of the arch and the elements of the key segment will again be delivered by the cable crane; closure of the superstructure is done by means of derrick erection. The deck of the bridge will be welded in the workshop upside down in about 8 meters long sections, because the welding points in the final structure are mainly located under the bridge. When the job is completed, the sections are turned around and delivered to the next stage of the process. At the point when long steel sections are prepared, the steel deck will be pushed on top of the segments. After this a derrick crane will be set on top of the deck. The derrick will extend the curve fragment from deck level to the erection of front of the curve. Deck erection will continue all the while with the erection of curve. Both curve and the deck cantilever unreservedly by up to 48m. At the point when the following curve dock area is reached, brief links will be introduced to help the curve, and the new curve wharf will be built on the free end. The superstructure would then be able to be upheld by curve dock, until the last curve wharf is reached. The absolute last curve range of the curve and the components of the key fragment will again be conveyed by the link crane; conclusion of the superstructure is finished through derrick erection. The deck of the extension is halfway straight skyline and part of the way in bends. It is situated on a progress bend with evolving span. Development is hence being done in stages following the progressive change in the arrangement. The deck of the extension will be welded in workshop about 8m long segments, on the grounds that the welding point in the last construction are predominantly situated under the scaffold.

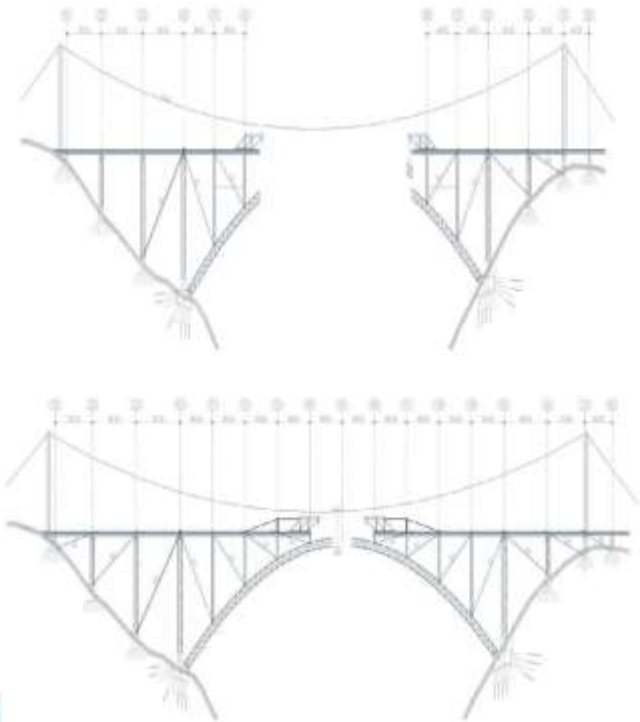

Fig 2: Typical arch erection by derrick crane.

X. DESIGN BASIS AND EXCEPTIONAL DESIGN PARAMETERS

10.1 Design Basis And Standards

Design Basis was already established by Indian Railways at the tender stage in 2004.This document included standards, load definitions, load parameters and load combinations, etc. It is noteworthy that the design method for steel structures was the India Service Load Design Method (Allowable Stress Design) and for concrete structures the Ultimate Limit State Design Method. After signing the contract, the Design Basis was updated, but it took a long time for the final Design Basis was agreed upon. The final Design Basis was signed in 2010. In the final design work the National Codes of India, Indian Railway Standards (IRS), Indian Road Congress (IRC) recommendations and Indian Standards (IS) had to be used but also international standards for instance for steel structures British Standards (BS) and even AASHTO and Eurocodes could be used. Although international codes could be considered, BS:5400 Part 3 – Design of Steel Bridges - was preferred for steel design. Also fatigue assessment was done as per BS: 5400 Part 10 – Code of Practice for Fatigue. Structural deformation limits had to be taken from UIC 776-3R – Deformation of Bridges. Ductile detailing of reinforced concrete structures RCC should be done as per Eurocode.

10.2 Main Loads

Basic rail loading is as per MBG: 1987 from the Indian Codes (Modified Broad Gauge Loading specification). Dynamic Augment (CDA) was taken from IRS Bridge Rules for the deck and piers, for arch there was no CDA. The deck was designed for two traffic arrangements: in the beginning, one track will be installed in the middle of the deck, but in the future, the track can be removed and the deck can be furnished for two tracks. Braking and Acceleration loads were taken from IRS Bridge Rules. The bridge was designed for seismic loads according to IS 1893, Part 1, 2002 – Criteria for Earthquake Resistant Design of Structures - Zone V and site-specific spectral studies as carried out by IIT, Roorkee. A challenging 50% of this seismic loading had to be considered in the erection stages. Because of the high altitude of the deck, complex terrain and anticipated lateral movement of the superstructure caused by wind the following wind tunnel models and tests were carried out in the very early stage:

a) Terrain model
b) Static/aero-elastic section model of the deck and static section model of the arch
c) Full aeroelastic model.

The analytical wind response computation was done by multimode frequency-domain analysis by taking into account the results of the terrain and section model tests. Static equivalent wind loads Were sent to structural designers to use in the design of the in-service bridge and construction stages. Finally, the analysis and wind resistance of the completed bridge were confirmed with a full aeroelastic model test. Static equivalent wind loads were sent to structural designers to use in the design of the in-service bridge and construction stages. Finally, the analysis and wind resistance of the completed bridge were confirmed with a full aeroelastic model test Partial safety factors and load combinations for reinforced concrete structures were taken from the Indian Railway Standard, but for steel structures, these were taken from British Standards slightly modified.

10.3 Some Exceptional Load Configurations

The Design Basis included some exceptional load configurations which were basically quite demanding for some structural components.
Blast Load had to be considered in the design. There were two scenarios of blast taking place on the deck or in close proximity to the foundations:

- Blast occurring at ground level at a near distance of the face of the pier/abutment.
- Contact blast occurring at any point on the steel deck with a train running on the center track of the bridge deck.

No damage to the arch trusses and no collapse for the bridge span under the above scenarios were allowed. Any damage to the structure has to be repairable so that it can be restored to its original serviceability requirement. In the deck, this led to the solution where a sacrificial steel net was designed on the deck to ensure minimum damage to the main superstructure. Another special design requirement was the Structural Redundancy of major elements. In this configuration structural redundancy of structures was assessed by removing critical bridge elements one by one as follows:

- A single element of one of the arch trusses was removed one by one from the structural model. The effect of the removal of one chord of the arch truss (one box of eight boxes) or one diagonal member of the arch truss had to be studied.
  One train passing at low speed had to be considered at the time of redundancy.
- The effect of a collapse of piers one by one should be checked using the ULS method.

XI. ANALYSIS MODELS

Chenab Bridge has been modelled in multiple ways at various design phases. The main calculation model used for the global analysis and erection stage analysis is set up in SOFiSTiK and was continuously updated to the latest software version during the course of the project The purpose of this model is to obtain global action forces and displacements as well as detailed design forces for the arch and trestles. Beam elements are applied as a standard The chords of the arch are modelled by two separate longitudinal spines each, which are connected by K-bracing elements to replicate the true stiffness for lateral loads and torsion. For the analysis of specific load conditions such as the loss of members, the K-bracing elements are replaced by actual plate elements allowing a study of the local behavior and residual capacities. This more complex model has not been employed in the analysis of other load conditions as no necessity existed and for the benefit of faster computation, especially during the erection phase where reaction time by the designers was of the essence. As the main arch is being filled withConcrete after its closure, the beam elements of the arch chords are modelled with composite cross sections, the partial materials are activated in line with the actual erection procedure. All structural elements in the models are split as a minimum according to the fabrication units to enable their activation in accordance with the erection process or for any side studies. Most elements are further subdivided at intervals sufficient to understand the development of action forces along the overall member. Hence, the same basic model could be used for the global analysis at the service stage and for the detailed erection stage analysis. The global analysis model was supplemented by local FE models for the design of particular elements such as the central shear key and the wind bracing connection details. For the erection stage analysis, temporary structural elements were implemented in the global model, namely the temporary stays and the temporary towers on top of the main pillars, some critical erection operation involved a number of small steps, in particular the installation of the first set of temporary stays and even more so the closure of the arch. In order to provide the site with data for the various sub-steps of these operations, models were split off the overall erection stage analysis and supplemented with further detail. Following the division of work between the designers, a second analysis model was set up for the detailed design of the land piers and the superstructure. This model was set up in the software LUSAS. The availability of two entirely separate models within the design team permitted a valuable comparison of results. Apart from such internal verifications and corresponding design checks, a full independent proof check of the design and analysis has been carried out on this National Project.

XII. STRUCTURAL DESIGN

Chenab Bridge is designed for a service life of 120 years. Steel grades used in the structure are E 410 C according to IS 2062 for the arch and piers (fy = 410~380 MPa depending on plate thickness), and E 250 C (fy = 250~230 MPa) for the superstructure. The superstructure is an open girder section, while elements of the arch and piers are typically box sections to facilitate bolted splices as site welding was not allowed on the project, Figure 16. Plate thicknesses are specified between 12 mm and 40 mm as a standard, and up to 70 mm for highly stressed members and gusset plates. Bolted connections are designed to be non-slipping at SLS and acting in bearing at ULS. The bolts are high-strength friction grip (HSFG) bolts grade 10.9 HSFG according to BS 4395, with typical sizes M30 and M36. The main boxes of the arch are filled with self- compacting concrete. This decision was taken in order to improve the robustness and the dynamic performance of the structure. Composite action is ensured by providing shear studs and small-diameter rebar stirrups inside the steel boxes. An added benefit of the infill concrete is the prevention of local buckling, thus, allowing higher utilization of the arch main chord. Casting was tested on a mock-up of an arch section, with a focus to ensure the concrete quality and avoid any air entrapments. Temporary bracing of the arch boxes for fresh concrete pressure was foreseen but eventually avoided by the contractor's refined procedures, concrete mix, and associated analysis. Only the wind bracings of the arch and a small quantity of secondary members are formed using pipe sections. Pipe sections were not preferred on the project as they are difficult to source in India, and not ideal to connect by bolts. However, the complex 3D geometry of the wind bracings was easier to achieve by using circular members.

XIII. ESTIMATION OF QUANTITIES

The project involves various major construction activities, each requiring significant quantities of materials and work. These include excavation, concreting, shotcreting, rock bolting, steel fabrication, and bolt installation. The table below summarizes the quantities associated with each activity, providing an overview of the project's overall scope.

Table no 1: Estimation of Quantities

SL NO	DISCRIPTION	QUANTITY
1	Excavation	1,002,658 m^3
3	Concreting	70,193 m^3
4	Shotcreting	76,280 m^2
5	Rock bolting	66,684 m
6	Fabrication and Erection of steel structural steel	31,062 MT (Metric tonne)
7	Installation of HSFG Bolts	306,312 pieces

XIV. CONCLUSIONS

The Chenab Bridge project stands as a monumental achievement in the annals of civil engineering and infrastructure development, not just in India but globally. Spanning the formidable Chenab River in the challenging terrain of the Himalayas in Jammu and Kashmir, this bridge exemplifies the triumph of human ingenuity, perseverance, and advanced technology over nature's most formidable obstacles. Upon completion, the Chenab Bridge will hold the distinction of being the world's highest railway bridge, rising 359 meters above the riverbed taller than the Eiffel Tower redefining standards in bridge construction and structural engineering. Designed to withstand extreme weather conditions, seismic activity, and even potential terrorist threats, the bridge is a paragon of resilience and innovation. Engineers faced countless challenges from treacherous geological conditions to logistical constraints and security Concerns yet they employed cutting edge techniques such as incremental launching, advanced seismic dampers, and corrosion-resistant steel to ensure both safety and longevity. The Chenab Bridge is not just a technological marvel but also a symbol of strategic importance. It plays a pivotal role in enhancing connectivity in Jammu and Kashmir, linking remote regions with the rest of the country and facilitating economic development, social integration, and defense logistics. It is a cornerstone in the Udhampur-Srinagar-Baramulla Railway Line (USBRL) project, which is set to transform the transportation landscape of the region by providing all- weather rail connectivity. Furthermore, the project has contributed significantly to local employment, skill development, and the upliftment of the regional economy during its construction phase. It has also set a benchmark for environmentally conscious engineering, with efforts made to preserve the fragile Himalayan ecology and minimize the environmental footprint. In conclusion, the Chenab Bridge is more than an infrastructural asset; it is a symbol of national pride, a testament to India's growing engineering prowess, and a beacon of connectivity and progress. As it opens new doors for tourism, commerce, and communication in the region, it also inspires future generations of engineers and planners to dream bigger, build stronger, and innovate further. The success of this project heralds a new era of infrastructure development in India bold, resilient, and visionary.

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