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Steel versus Concrete versus Prefabricated Structures as Sustainable Building Materials concerning Cost, Time, and Space for Major Infrastructure Projects

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ABSTRACT

A contrast and comparison of the various building materials with the actual construction of the Bhawar Kuan Flyover in Indore, Madhya Pradesh was researched. This enabled an on-site study of the various materials used according to their properties. The best mix was adopted given the cost, variations in temperature of the site, and the feasibility of transporting the materials. The problems faced during construction were adequately addressed taking into account the sentiments of the people e.g. position of a mandir as well as ensuring that the traffic was not disturbed at this busy intersection.

Keywords: malleability, ductility, tension, shear force, stress, compressive stress, tensile force, elasticity, buckling

Research question: An attempt would be made to understand and analyze the use of steel, concrete and prefabricated structures in the construction of major infrastructure projects like highways, bridges, and metros. To understand the impact of these major building materials it would be necessary to research the project depending on weather conditions, durability and cost-benefit analysis involved. What are the reasons for different structures being use ? Do they depend upon whether the project is in a developed or a developing economy? What is the longevity of the project? Would 'time' be an important aspect in determining the type of material that is finally selected? These and other similar questions related to the strength of the material as well as the structure that is being built will be addressed in the course of this paper.

Introduction:

In general building materials could be divided into two categories; natural and synthetic. Materials like stone and wood are natural while steel concrete prefabricated plastics are man-

ISSN: 2455-8834

Volume:09, Issue:10 "October 2024"

made. Each of these materials has unique properties which make it ideal for specific construction projects. In recent times when climate change has become an extremely important pressing issue, sustainable building materials are considered due to their minimal negative environmental impacts throughout their life cycle right from extraction to disposal or reuse.

The main objectives of infrastructure companies are to layout, develop, construct, build, acquire, erect, demolish, re-erect, alter, modify, repair, and remodel in connection with highways bridges flyovers roads metro, etc.

It has been researched that materials like reinforced concrete which is manufactured away from the actual construction site indicates that it is impervious to oxidation, plant or animal intrusion, erosion from fire, water, and wind would then last for 10,000 years.

The reason that infrastructure development is important for an economy is because it facilitates trade, economic growth, human development, and productivity across many sectors of the economy.

The four pillars of infrastructure which are also the key analytic elements of sustainable theory for civil infrastructure are;

- Environmental
- Technical
- Economic
- Social

Fig 1) Important factors to be considered for the delivery of a project

Source: Google Images

ISSN: 2455-8834
Volume:09, Issue:10 "October 2024"

To understand the use of steel, concrete, or prefabricated structures in infrastructure projects, it is necessary to define various properties and strengths of the materials.

2) Definition:

2.1) Steel

Steel as a material has a very high 'strength' compared to concrete. This 'strength' is defined as 'the ability to withstand an applied stress or load without structural failure' (Byjus). Typical concrete is less than one-tenth as strong as strong as structural steel.

Table (1.1)

Material	**PSI [1]**	**Weight to strength ratio [2]**
Steel	25000-50000	85-90
Normal grade concrete	725-2000	10-20
Standard grade concrete	3600-6500	25-50
High strength concrete	7200-10000	60-80

[1] pressure that results when a 1-pound force is applied to a unit area of 1 square inch

Source: techtarget.com

[2] point at which a building will fail to support its weight under stress

Source: rhinobldg.com

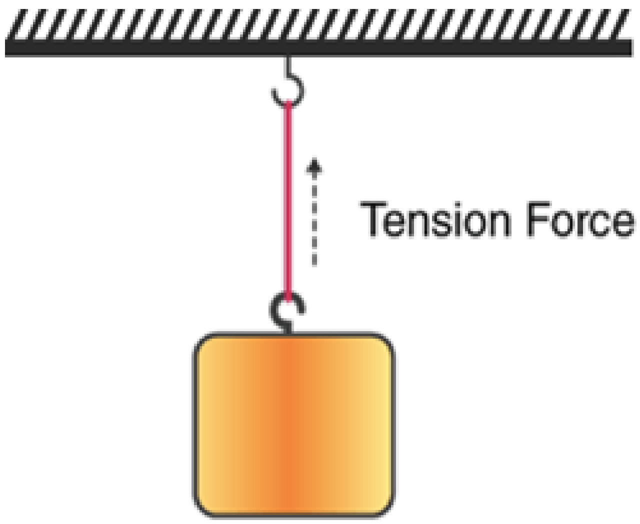
The properties of a material are measured by the following:

a) Tension: which is the force that is applied on the length of a medium mostly an elastic material like a rope.

ISSN: 2455-8834

Volume:09, Issue:10 "October 2024"

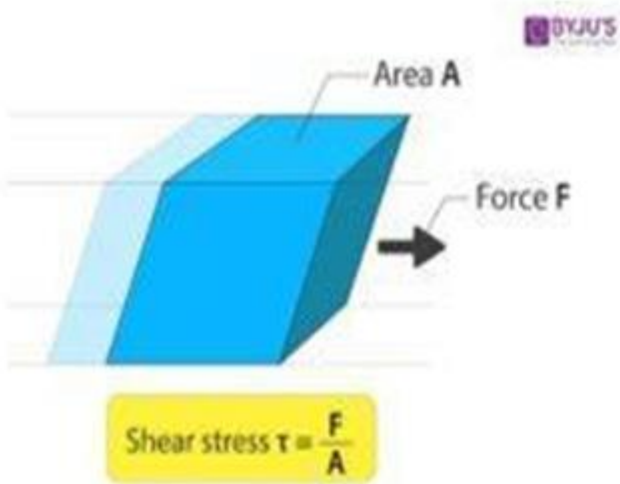
Fig 2: Depiction of Tension Force



Source: https://byjus.com/physics/tension/

b) Shear force: This is the force that acts parallel or tangentially on a surface which then causes the body to deform or slide.

Fig 3: Depiction of Shear Force on a Surface



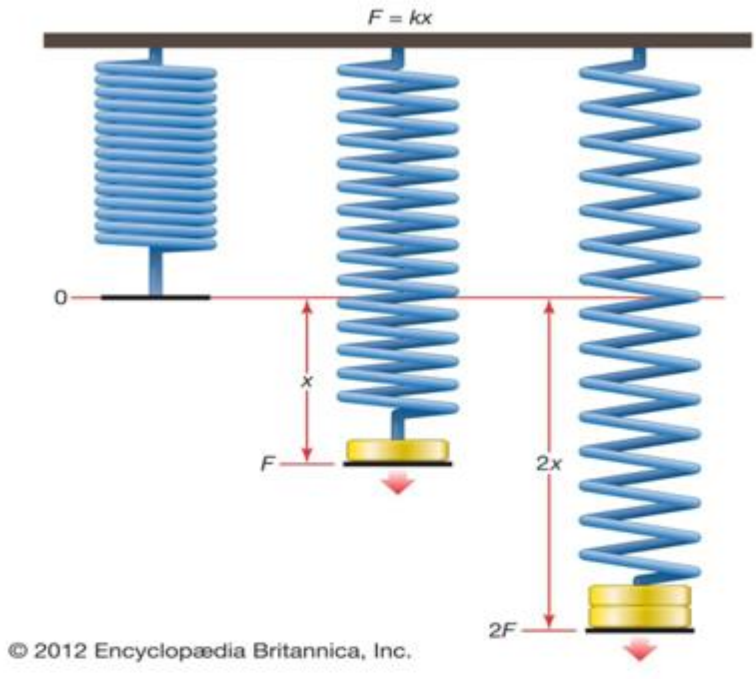
Source: https://byjus.com/physics/shearing-stress/

c) Good elasticity is the characteristic of a body that is deformed by a force and its ability to return to its original length, shape, and size when the force is eventually not applied.

ISSN: 2455-8834

Volume:09, Issue:10 "October 2024"

Fig 4: depiction of elasticity on a spring



Source: https://www.britannica.com/science/elasticity-physics

d) Tensile stress is the ratio between the force applied that stretches the body and the cross-sectional area of the body.

Fig 5) showing calculations of tensile stress

Stress

$$\text{Tensile stress} = \frac{\text{Tensile force}}{\text{Area of cross section}} \left(\frac{N}{m^2}\right)$$

$$\sigma = \frac{F}{A}$$

Source: https://alevelphysics.co.uk/notes/stress-strain/

e) Tensile force: the stretching force acting on the material

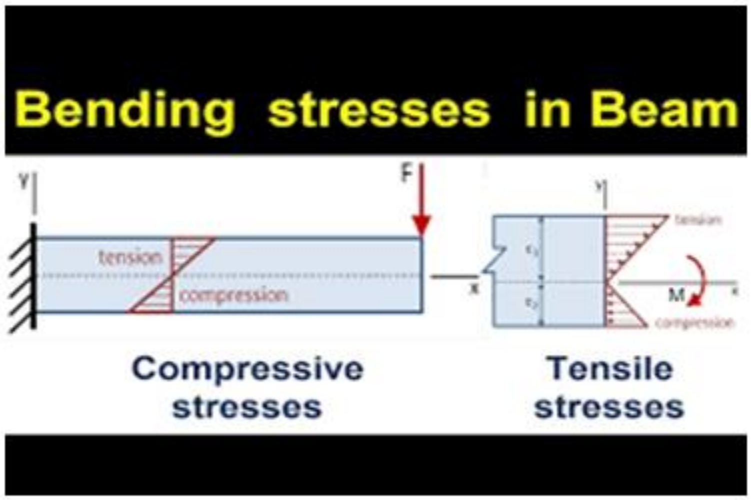
f) Compressive and bending stress: This is a combination of compressive and tensile stresses due to internal moment.

International Journal of Social Science and Economic Research

ISSN: 2455-8834

Volume:09, Issue:10 "October 2024"

Fig 6 Depiction of Compressive and Bending Stress on a Body



Source: https://www.youtube.com/watch?v=8aZezV8wdJg

g) Durability: is the ability of a physical product to remain functional, without requiring excessive maintenance or repair when faced with the challenges of normal operation over its design lifetime.

h) Malleability: is the physical property of a solid to bend or be hammered into another shape without breaking

Fig 7 representation of malleability in a metal

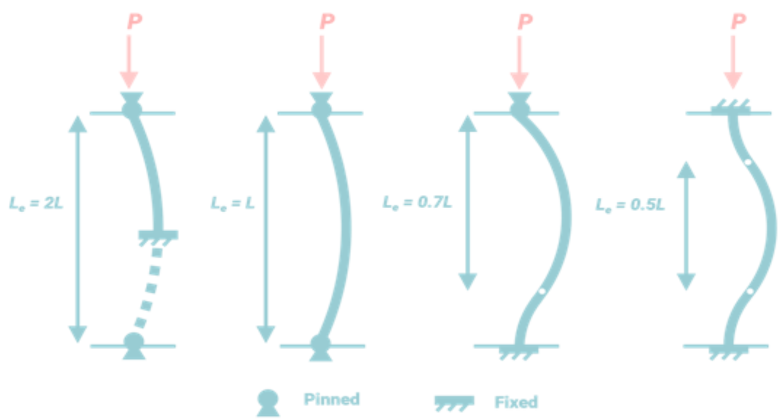
Source: https://sciencenotes.org/malleable-definition-what-is-malleability/

Buckling is the rapid change in the shape of the structure under a load higher than it can withstand

ISSN: 2455-8834

Volume:09, Issue:10 "October 2024"

Fig 8 representation of the concept of 'buckling' in steel structures

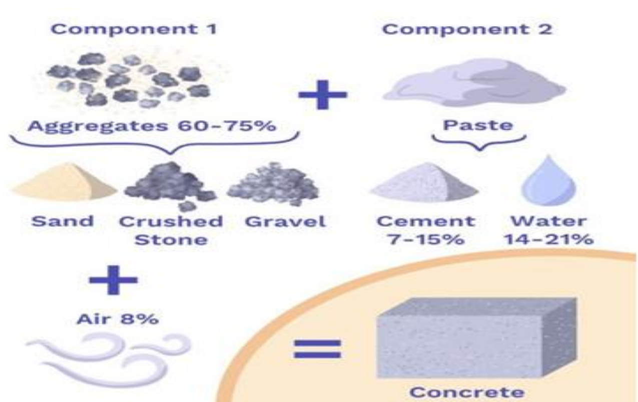


Source: https://tribby3d.com/blog/column-buckling/

2.2) Concrete

Concrete is a mixture of Cement water and materials like sand and gravel that hardens over time to create a solid strong substance. It is used in construction projects because it is affordable, durable, and can be molded. The aggregate, which is normally sand and gravel, is a hard, chemically inert particulate substance.

Fig 9. Composition of concrete



Source: https://climatescience.org/advanced-concrete-climate

Concrete as a building material was prevalent amongst the ancient Babylonians where the bonding substance was clay. The Egyptians developed a substance that closely resembles present-day modern concrete by using lime (CaO) and gypsum. In 1824, the English inventor Joseph Aspdin burned and ground together a mixture of limestone and clay. This mixture is

ISSN: 2455-8834

Volume:09, Issue:10 "October 2024"

called Portland cement which has remained the dominant cementing agent in concrete production.

Aggregates are designated as either fine (ranging in size from 0.025 to 6.5mm) or coarse (6.5 to 38mm). All aggregate materials must be clean and free from small particles or vegetable matter, as even small quantities of organic soil compounds result in chemical reactions that seriously affect the strength of the concrete.

Concrete is characterized by the:

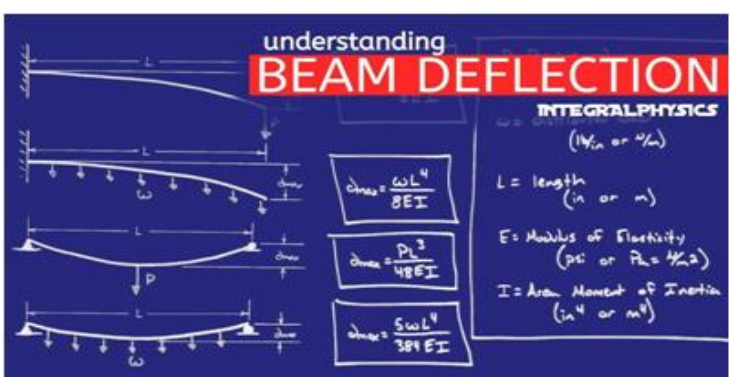
- Aggregate used
- Cement used
- Method of production

In ordinary structural concrete, the character of the concrete is determined by water to cement ratio. The lower the water content, all other factors being equal, the stronger the concrete. The idea is that the mixture must have enough water to ensure that each aggregate particle is surrounded by the cement base such that the spaces between the aggregate are filled and that the concrete is liquid enough to be poured and spread effectively.

Durability

This is defined as the amount of cement concerning the aggregate and is expressed as a 3-part ratio between cement: fine aggregate: and coarse aggregate. Whenever strong concrete is needed the amount of aggregate is reduced.

Fig10) figure representing beam deflection



Source) Google images

ISSN: 2455-8834

Volume:09, Issue:10 "October 2024"

Strength

This is measured in pounds per square inch or kilograms per square centimeter of force needed to crush a sample of a given hardness. This is affected by environmental factors, especially temperature and moisture.

Tensile stress

If concrete is allowed to dry prematurely it can experience unequal tensile stresses that in an imperfectly hardened state cannot be resisted. To prevent this, a process known as curing is essential. The concrete is kept damp for some time after pouring to slow the shrinkage that occurs as it hardens.

2.3). basic requirements of prefabricated structures used for infrastructure development

Deflection

Deflection is the bending of joists, trusses, or rafters associated with overload structures. The knowledge of deflection due to bending allows engineers to predict and control structural behaviors under various load conditions, enhancing the safety and durability of the structure.

Footfall vibrations

The dynamic forces that cause the structures to vibrate. The frequency of footfall is as follows-

- Walking: 1.5-2.2 Hz
- Running: 2-4 Hz
- Descending stairs: 1-4.5 Hz

Different ages of concrete have different vibration limits. The vibration limit of concrete over 28 days is in the range of 70mm/s to 140mm/s.

Traffic vibration is mainly due to heavy trucks passing at a relatively high speed on a road with an uneven surface profile. This causes dynamic excitation which generates waves propagating in the soil and impinging on the foundation of nearby structures.

International Journal of Social Science and Economic Research

ISSN: 2455-8834

Volume:09, Issue:10 "October 2024"

Fig11) Standard Requirements as required by law for prefabricated infrastructures

Standard	Parameter	Limits	Conditions of use
		Effect on structures	
DIN 4150-3	peak particle velocity	3 mm/s	(very) sensitive building
	(the higher component)	5 mm/s	dwelling place
SN 640 312a	peak particle velocity	3 mm/s	frequently excited sensitive building
	(the higher component)	6 mm/s	normally excited building
		Effect on persons in building	
ISO 2631-2	weighted *rms*	$0.315\,m/s^2$	not or a little uncomfortable
	acceleration	$2\,m/s^2$	extremely uncomfortable
USDT	*rms* velocity	0.10 mm/s	residential area frequent (>70 passbys per day)
		0.26 mm/s	residential aera infrequent (<70 passbys per day)
DIN 4150-2	weighted dose	0.15 mm/s	residential area
	$KB_{F,\max}$	0.10 mm/s	sentitive area

Source: https://www.google.com/url?sa=i&url=https://www.researchgate.net/figure/Standard-analysis-summary-for-ground-borne-vibration-assessment

Temporary load: several things have to be taken into account while building infrastructure using prefabricated material for the load imposed by various construction machinery and materials on the area earmarked for the project.

Low temperatures adversely affected the strength of the material. To compensate for this, an additional aggregate (CaCl) is mixed with cement. This accelerates the setting process which in turn generates heat sufficient to counteract moderately low temperatures. Large concrete forms that cannot be adequately covered are not poured in freezing temperatures.

Plain concrete does not easily withstand stress such as wind, earthquakes, vibration, and other bending forces, leading to it being unsuitable for many structural applications Concrete is weak in bending, shear, and torsion and thus, not recommended for great comprehensive strength and weight.

ISSN: 2455-8834
Volume:09, Issue:10 "October 2024"

Table 2: Comparison of properties of concrete and steel

	Concrete	**Steel**
Strength in compression	Good	Good but buckling occurs
Strength in shear	Fair	Good
Durability	Good	Corrodes if not protected
Fire resistance	Good	Poor - rapid loss of strength at high temperatures

Properties

The four main properties of concrete are:

- Compressive strength
- Workability
- Durability
- Tensile strength
- Volume stability
- Impermeability

The seven physical properties of concrete material that are required for mixing are:

- Shape and texture
- Size gradation
- Moisture content
- Specific gravity

- Reactivity
- Soundness
- Bulk unit weight

2.3) Prefabricated

Prefabricated construction is the process of manufacturing different components of a structure in a factory or manufacturing facility away from the actual site and then transporting the complete set of components to the construction site for the assembly of the structure. Off-site construction provides better provision for planning and manufacturing building components in another place. These materials are strong, financially viable, and environmentally friendly. The prefabricated materials used are normally

- Panelized wood framing that is built from laminated timber and covered with plywood is used in the construction of roofs.

Fig 12) image showing a panelized wood frame

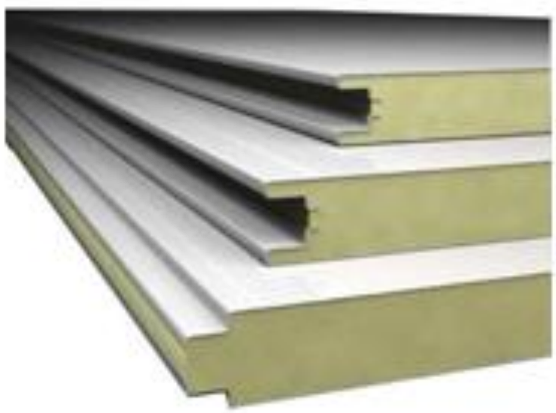
Source https://www.google.com/url?sa=i&url=https://www.residentialproductsonline.com/4-panelized-systems-save-time-and-labor&psig

- Sandwich panels, consisting of an insulating core material that is covered with thin facings of materials on the two sides stuck firmly. The insulating materials and facing materials used can be foam, paper, cloth, rubber, concrete, plywood, stainless steel, etc.

ISSN: 2455-8834

Volume:09, Issue:10 "October 2024"

Fig 13) image showing sandwich panels



Source: Google Images

- Steel framing which are strong and durable framing systems that is used to construct buildings.

Fig 14) Image showing the building of a steel frame

Source: Google Images

- Concrete systems provide more versatility and save time; despite being heavy their usage improves the aesthetics of the structure.

ISSN: 2455-8834

Volume:09, Issue:10 "October 2024"

Fig 15) image showing a concrete structure

Source: Google Images

An important factor that has to be kept in mind while manufacturing fabricated structures is that they have to be within the "codes of practice and guidelines" that are set up for various countries. There are frameworks under 'limit state design' that pre-fabricated structures have to follow. The three main design criteria are

1. Stability
2. Serviceability
3. Strength

The above three are the basic criteria that are followed all over the world; the only difference may be the terminology that is used. For e.g., some countries use 'ultimate limit' instead of strength design.

The 'load factor' is also applied in a prefabricated structure as is the case with any structural traditional design. The usage and importance level are determined according to structural design and the relevant codes of practice prevalent in a country.

The arrangement of structural elements will be of a different approach as compared to the traditional conceptual structural design. The unique requirements of a prefabricated structure that must be considered are:

1. The strategy for transportation, lifting, and handling of the prefabricated units within the manufacturing facility and afterward following a Design for Manufacturing (DFM) and Design for Assembly (DFA).
2. The arrangement of structural elements and frames could be fully or partly automated within an offsite manufacturing facility, to obtain outputs with greater accuracy and minimization of waste generation, energy usage, and emissions.

ISSN: 2455-8834

Volume:09, Issue:10 "October 2024"

3. Certain structural elements would need to be strategically placed in a way to assist the planned lifting process. For e.g., lifting connectors can be fitted into the structural columns of modules and panels using welded nuts.

4. There would be certain limitations imposed on a structural design that would be dependent on the method of transportation, for e.g., the trailer would need to have a level floor bed so that the modules could be placed stably on the transport vehicle.

3) Advantages of steel concrete and prefabricated materials used in construction

3.1) Steel

Steel has a tensile strength making it capable of withstanding heavy loads and forces without deforming or collapsing, leading to the long span of structures as well as providing stability and safety. It is also lighter than an equivalent concrete structure and with it comes the reduced load on foundations leading to smaller foundations and thus an ability to perform better under certain ground conditions. The malleability of the material allows architects to develop and explore new ideas and products. It also can bend leading to curves being built with exact specifications.

The other specific advantages of this material are -(https://www.steel.org.au)

- Speed of construction
- Value for money
- Safety
- Robustness and ductility
- Prefabrication
- Reduced weight
- Configuration adaptability
- Sustainability

3.2) Concrete

The advantages of using concrete as an effective construction medium are-

- Cost-effectiveness

ISSN: 2455-8834

Volume:09, Issue:10 "October 2024"

- Immense strength and durability
- Hardens easily
- Can be molded easily and effortlessly
- Does not require much energy while production
- Water resistance
- Temperature resistance
- Consumes waste products of the industry

3.3) Prefabricated

- Reduces construction time
- Reduces risk of damage
- Ensures quality control
- Minimizes the carbon footprint
- Affordable
- Streamlines the construction process
- Reduces on-site accidents
- Easy to add and dismantle

4) Case study of Bhavarkuan flyover Indore, Madhya Pradesh, India

The agreement with the government concerning:

A. The time span (18 months)

The time span kept being extended due to the existence of various water pipes and leakages which had eventually to be shifted so that the residents still had access to this facility and the flyover could then be built without further issues.

B. Materials used in construction

The material is a mix of steel and pre-fabricated concrete and other materials. The steel was used exactly over the crossing, which is indicated by the green color in the figure 2.8. There also was a bus rapid transport system (indicated by the blue color on Fig 2.8) so steel was also used to not disrupt this system.

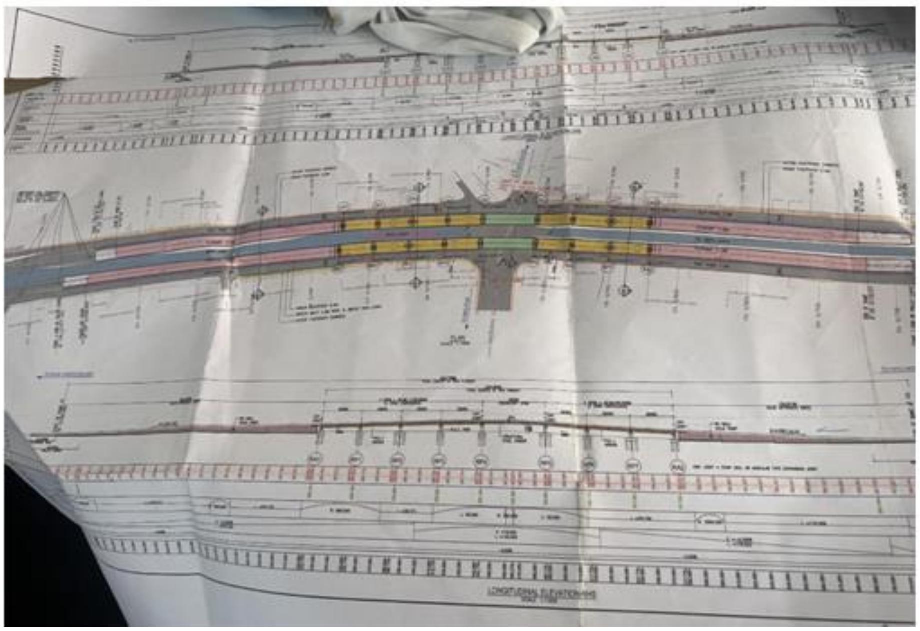
ISSN: 2455-8834

Volume:09, Issue:10 "October 2024"

There was also a temple in the way which could not be demolished for religious reasons so steel structures had to be made to go over it.

The steel structure did not require to be held up with columns so it would not disrupt the flow of traffic that's why steel was used over the crossing.

Fig 16) showing plans of the flyover with respect to different materials



Source: Own research

C. Other safety measures

Helmets for all construction workers and road signals for the safety of cars to alert drivers were put in place. Also, work being done on the crossing was scheduled at night to avoid accidents and traffic jams.

D. Any other important factors taken into account

The main obstacle that had to be taken into account was to save the 'mandir' while keeping the utility of the flyover intact.

Besides the saving of the mandir, there were other sanctions for sewage, electricity, and other basic amenities that had to be addressed during construction. The additional delay was in obtaining sanctions to repair the water line leakages which took 3-4 months.

ISSN: 2455-8834

Volume:09, Issue:10 "October 2024"

Despite the above disruption during the construction process, adequate care was taken for cars and pedestrians by lighting up the area giving clear indications of various diversions.

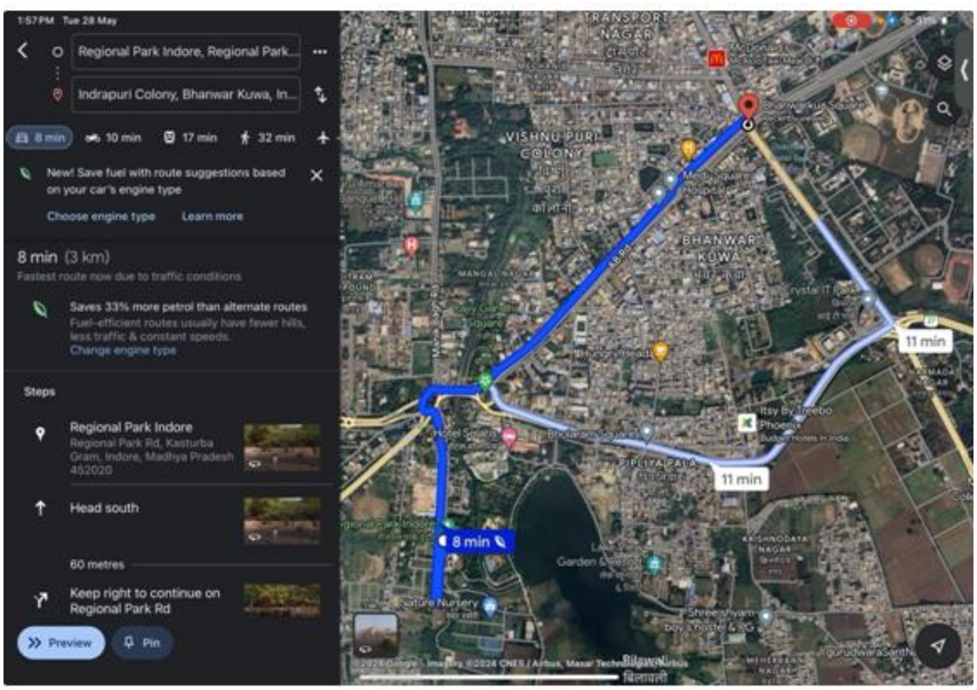
4) Construction of the flyover

4.1) Off-site construction

Prefabricated cabins and all amenities for the workers.

There were prefabricated structures which were made at the site as indicated in the figure below Type of materials used for various parts of the flyover were all assembled off-site which was at a distance of 3 kilometers from the actual place of construction. While assembling the various structures extreme care was taken to follow ISIS standards as stated by the government bylaws document. Besides stringently following all rules and regulations there were government officials present who further ensured that all mandatory quality standards were being followed and built according to sanctioned plans. These rules were adhered to for labor contracts for their safety and other social security obligations. Insurances were taken for both workers and equipment in the form of group insurance against any untoward mishap.

Fig 18) showing distance of the prefabrication site to the actual site



Source: google maps

ISSN: 2455-8834
Volume:09, Issue:10 "October 2024"

5) Images at Various Stages

Stage 1- temporary placement of the crash barrier on top of the bridge

Fig 19) showing stage 1 of construction

Stage 2 - Putting the concrete cement mixture at the side of the crash barrier

Fig 20) showing stage 2 of construction

ISSN: 2455-8834

Volume:09, Issue:10 "October 2024"

Stage 3 - curating arrangement of cement by gunny bags at the site

Fig 21) showing stage 3 of construction

Stage 4 - Putty and primer being applied on the crash barrier

Fig 22) showing stage 4 of construction

ISSN: 2455-8834

Volume:09, Issue:10 "October 2024"

Stage 5 - Final painting of the crash barrier

Fig 23) showing stage 5 of construction

The source for all of the above is actual photographs of the Bhawar Kuan flyover in Indore, Madhya Pradesh, India.

The type of concrete mix that was used in the making of the flyover was of the following specifications:

- M40 mix was used for pilling (the pillar stage)
- There were trial cubes made which underwent malleability and ductility tests to ensure the strength and the weight that the flyover would be able to withstand.
- Care was taken that the concrete mix used in the making of the flyover was of the strength that was specified in the tendering process of the flyover. The tendering process went through a technical as well as financial scrutiny before it was awarded.

ISSN: 2455-8834

Volume:09, Issue:10 "October 2024"

4.3) Additional problems faced during the construction of the project

Besides the mandir and water pipeline leakages, the other main issues were primarily due to finances not being released by the government on time. Every time there was a delay the work stopped and the cost increased.

The area on which the flyover was being constructed was a congested one, resulting in major work being done during nighttime. This added to the safety concerns of both the workers as well as the traffic on that road from midnight to 5 am. This added to extra safety measures to prevent any untoward incidents. To give an example of the extent of safety measures that were taken, when any electrical work was being undertaken a system of 'kill switch' was placed at various points with proper taped cables at junctions such that no 'electric shock' could be conducted. All weather generators were placed so that in case of any electric power cuts work could continue uninterrupted.

Conclusion

The flyover was constructed according to specifications as stated in the tender document when the contract was awarded. It followed the basic principles that have been indicated in the theory stated above. All principles for materials and their properties were adhered to ensure longevity, safety, durability, and aesthetics. Various problems were faced in the construction of the flyover which led to certain delays for cost and time. These were not fully anticipated at the time of construction. They were adequately addressed keeping the sentiments of the people in mind (specifically, the position of the mandir) as well as ensuring smooth movement of traffic during the construction of the flyover.

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ISSN: 2455-8834

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