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# Constructability Assessment of Climbing Formwork Systems Using Building Information Modeling

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Abstract

Vertical development is the ideal solution to meet the demand of land for the fast growing urban population in India. It is the construction of tall structures such as high-rise buildings, sky scrapers and sky towers etc., rather than constructing laterally to accommodate large population in quiet a lesser area. However the construction of high-rise buildings are highly complex and requires advanced construction techniques and equipment. One of the most important requirements is the advancement in forming technology. Though the conventional or traditional method of forming high-rise building is economical, it suffers seriously on the time, quality, safety and sustainability factors. Therefore, the advanced systems known as climbing formwork was introduced later. The climbing formwork is relatively new technology developed from the slipform in late 1960s. Unlike the developed countries, the practice of climbing formwork is adopted only in the specialized construction projects in India. The reason being, lack of awareness about the climbing formwork among many construction personnel and misconception about the erection and operation processes. Thus to reinforce the importance of climbing formwork in the Indian construction, a firm research is carried out on the selection and operation of different climbing formwork using constructability survey. A valid comparison of different climbing formwork with the conventional formwork is done for the lift core-wall in the 20 storey high-rise building model using Building Information Modeling (BIM). From the developed 3D BIM model, the cost, time, quality, safety and sustainability factors of both conventional and climbing formwork are explored in detail by quantitative and qualitative indices. The constructability factors associated with the conventional and different climbing formwork systems are generated.



Keywords: Building Information Modeling; climbing formwork; constructability; high-rise building; vertical development

## 1. Introduction

India measures 3,214 km from North to South and 2,933 km from East to West. It has a land frontier of 15,200 km and a coastline of 7,516.5 km. It has a population of approximately 1.21 billion people (2011 Census), which is the second most populous country in the world. Although India occupies only 2.4% of the world's land area, it supports more than 17.5% (2011 Census) of the world's population. The population of India is forecast to be 1.63 billion people in 2050, which is expected to exceed China (1.4 billion people in 2050).

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For the past 30 years, unlike the rural regions, the population of urban regions is increasing rapidly due to the factors like modernization, increased employment opportunities and so on. At present, the percentage of land use in the urban regions is increasing drastically. Most of the agricultural lands are getting converted into construction grounds due to unavailability of land. This is the major setback for the sustainable development.

To cater the needs of land for the growing population, the best solution is the vertical development which is the construction of tall structures such as sky scrapers and sky towers, etc. Thus to accommodate the future growing population, there should be reduction in the lateral construction and instead vertical development is promoted. However, the implementation of vertical development is not so easy since the construction of tall structures are highly complex and requires higher degree of construction techniques and equipments and thus it could not be achieved by the present ordinary construction methods and equipments. For the construction of high-rise structures, many critical factors have to be considered and the most important factor is the formwork operation, which influence highly on the construction time, cost and profitability of the project itself.

### 1.1. Formwork practice in India

For many years reinforced concrete construction is predominantly followed in India, thus the formwork plays a vital role in the Indian construction. The most commonly used type of formwork systems are the traditional or conventional systems made of dressed lumber and fabricated at site during construction as shown in Fig.1(a). They are also known as as-built formwork. Currently even for construction of wide variety of structures from small to medium sized projects, the conventional formwork systems are used. Quality, safety and economy are the three objectives of formwork construction [1]. The conventional formwork systems could account only for the economy aspects of form construction, thus the modern formwork systems known as Engineered or System Formwork Systems was developed later.

System Formworks are built of prefabricated modules (standard timber beams) with the metal frames and patented plywood sheathings. Since 1980, the concept of system formwork is improving tremendously due to the advancement in forming technology and fabrication process. New and innovative materials such as Plastic, FRP (Fibre Reinforced Polymer), Aluminium, etc., are used as an alternatives for the timber components as shown in Fig 1(b).

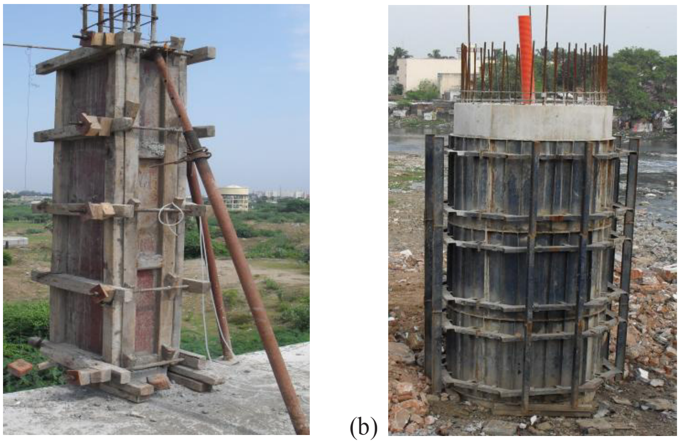
(a)  (b)

Fig. 1. (a) Conventional formwork system; (b) System formwork.

The two major advantages of system formwork over conventional timber formwork systems are as follows.

1. Speed of construction (reduced time in assembly and stripping)
2. Lower life-cycle costs (maximum number of re-use).

Though the system formwork has many advantages over traditional or conventional formwork, their usage in the Indian construction is very minimal. The reason being, lack of awareness, misconception among the Indian construction personnel, that these formworks are costlier and heavier, requirement of highly skilled labours and supervisors, requirement of specialised equipments for erection and assembly but in reality it is the most effective system [5].

Thus to reinforce the importance of adaptation of system formwork in the residential and commercial high-rise buildings, a firm research is carried out on the selection and operation of different system formwork and a valid comparison is done with the conventional formwork system. The system formwork adopted for this research is Climbing formwork systems, which is the development of slipform.

### 1.2. Slipform

The slipform was introduced in the early 1900 to construct tall and slender structures. It was made from timber and used with hand operated screw jacks, later the screw jacks are replaced by mechanical/hydraulic jacks. The slipform served as the best forming solution for building silos and grain elevators, etc., throughout the world but was introduced to residential and commercial high rise buildings in North America only in the late 1960 [4]. In India, only during the late 1970, this technique was incorporated in the construction of tall structures especially for the construction of cooling towers in thermal and nuclear power stations.

The formwork system uses a 1.06 m high steel panel which is held rigid with a steel framework. There are strategically placed yoke units. Attached in the yoke units are hydraulic climbing jacks which are passed through by black mild steel rods. These jack rods are cast in the wall and the jacks hoist up themselves at the rods as shown in Fig 2. The salient features of the slipform [2] are given in the Tab 1.

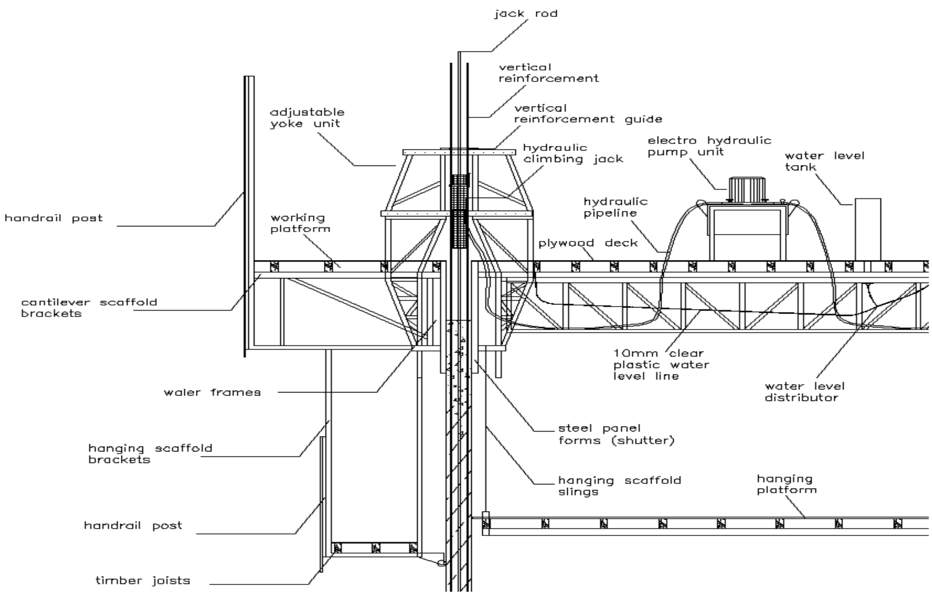



Fig. 2. Typical components of early slipform system.

Table 1. Technical aspects of Slipform

| Description | Criteria |
|---|---|
| Normal layer thickness | 200–250 mm |
| Normal Taper on forms | 3 mm |
| Normal Depth of forms | 1070 mm |
| Average Slip Speeds | 350–400 mm per hour |
| Design wind pressure | 1.635 kPa |
| Design wind velocity | 42.7 m/s (153.72 km/h) |
| Average lifting speed | 300 mm/hour |
| Average jack stroke | 25 mm |
| In 24 hour operation | 288 strokes per day |
| In 10 hour operation | 120 strokes per day |
| Max. General load on yokes head plates | 31.1 kN |

The major limitations of slipform are the concreting has to be done continuously; it requires lot of manpower, supervisors, it has bad dimensional efficiency (high tolerance), gruelling [2] and difficult to work because of the narrowness between the formwork and concrete, it has large number of connecting parts and so on. Thus a new formwork system known as, Climbing formwork system was developed later to overcome the drawbacks of slipform.

### 1.3. Climbing Formwork system

The climbing formwork is a forming method for tall structures in which concrete is poured into a continuously moving formwork [3]. The formwork is surrounded by a three-story-high platform on which workers stand, place steel reinforcing rods into the concrete and ensuring a smooth pour and finish the later part of finished concrete surface. The concrete form and working platform is raised together, by means of hydraulic jacks fixed over rail on the external surface as shown in Fig 3.

Fig. 3. Typical climbing formwork system for lift core wall construction.

### 1.4. Types of Climbing Formwork System

The Climbing formwork, sliding formwork, jump formwork are synonymously same and in some instances the horizontal Slipform, travelling formwork are also interpreted as climbing formwork system. They are generally classified based on the verticality of the construction as Horizontal or Inclined Climbing Formwork System [1] and Vertical Climbing Formwork System as shown in Fig 4. They are classified based on the mode of operation, as Climbing Formwork System, CFS (Crane-dependent System), Automatic or Self Climbing Formwork System, ACFS/SCFS (Crane-independent System), Semi-Automatic or Semi-Self Climbing Formwork System, SACFS/SSCFS (Crane-dependent only upto certain height).

(a) (b) (c)

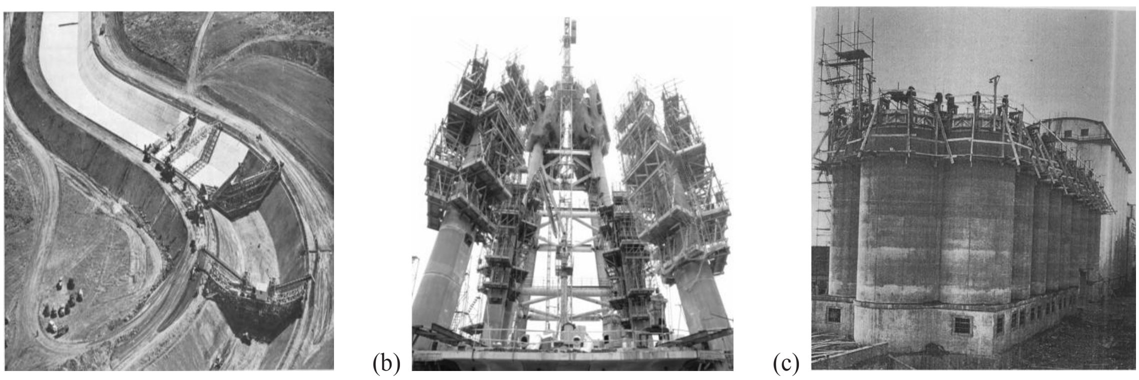


Fig. 4. (a) Horizontal Climbing Formwork System; (b) Inclined Climbing Formwork System; (c)Vertical Climbing Formwork System.

## 2. Research Methodology

The purpose of this research is to explore the various factors influencing the selection and operation of the different types of climbing formwork systems adopted in the construction of high-rise buildings from the constructability survey. Fifty complex constructions projects in India were considered for the Constructability survey.

This research also illustrates the construction and sequence of operations of the climbing formwork systems for the construction of lift core wall of 20 storey high-rise building using the 3D Model by Building Information Modeling (BIM) model.

This research concludes by bringing down the potential advantages of the climbing formwork systems over the conventional formwork system on the basis of cost, time, quality, safety and sustainability factors using qualitative and quantitative indices by a technique called Constructability. The detailed conceptual framework of this research is as follows.

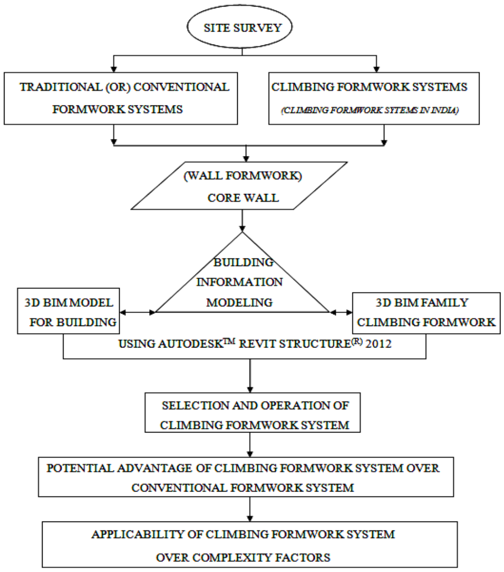



Fig. 5. Conceptual framework of this research

### 2.1. Constructability Assessment

Constructability Analysis is as an analytical, creative and strategic organization function focusing on the most important factor to the overall success of a Construction Project. The use of constructability analysis provides an opportunity for input from the constructability review to the construction personnel to insure that efficient, economical, and quality solutions are reached [8].

### 2.2. Constructability Survey

In order to perform constructability assessment, one should not only have sound knowledge on the concepts of constructability but also have adequate hand-on experience in executing a similar set of work for a certain period of time [8]. To acquire the knowledge and experience, adequate hand-on training on the field/industry is necessary for a particular period of time, for collecting work sampling, work sequencing, productivity, contracting procedure, material handling functions [8] and other constructability factors is known as Constructability Survey.

## 3. Constructability Assessment of Climbing Formwork Systems

The constructability assessment of climbing formwork systems involves the creation of 3D BIM structural model and 3D BIM formwork family files and gets amalgamated into a single 3D BIM model. The detailed description of the constructability assessment of climbing formwork systems are as follows.

### 3.1. 3D BIM model of the Structural Systems

The 3D BIM model for the structural systems considered for this research is the digital representation of 20 storey high-rise building (each floor has an area of 530/m$^2$) developed in Autodesk Revit 2013 as shown in Fig 5-6. To develop an adequate 3D BIM Model, floor plan and elevation drawings should be generated and validated in greater detail [6]. The 2D drawings necessary for the generation of 3D BIM Model of 20 storey high-rise building are in Fig 6-7.

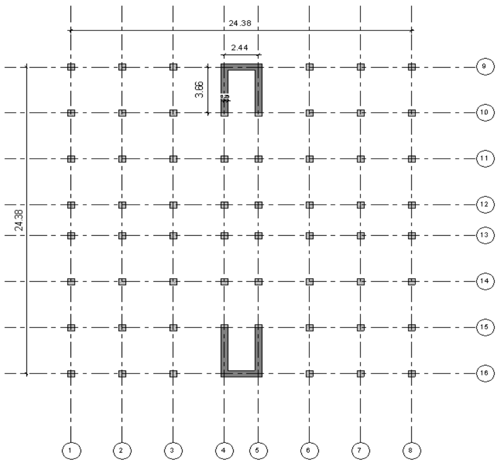



Fig. 6. 2D Floor Plan of the BIM model

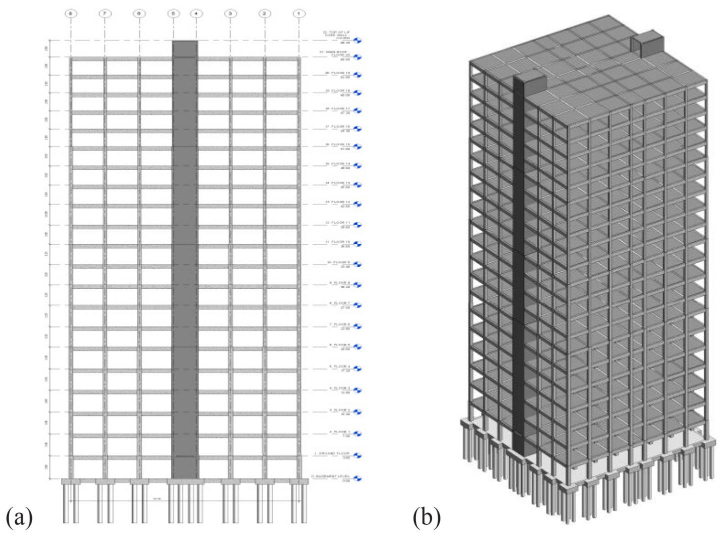
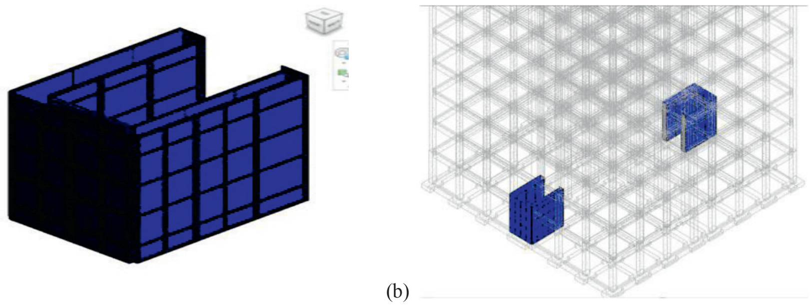



Fig. 7. (a) 2D North Elevation of the BIM model; (b) 3D Solid BIM.

### 3.2. 3D BIM model of the Climbing Formwork Systems

The detailed description of the creation of 3D BIM conventional and climbing formwork systems are as follows.



(a) (b)

Fig. 8. (a) 3D BIM Conventional wall formwork family file; (b) Importing the 3D BIM wall formwork family file into the wireframe model.

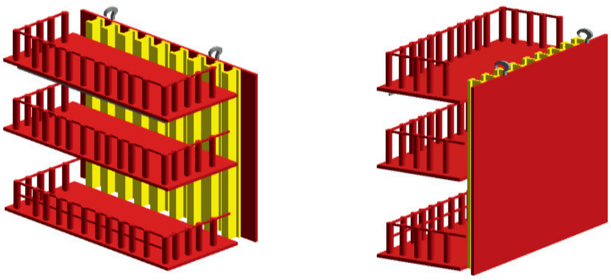


Fig. 9. 3D BIM climbing formwork system (crane-dependent system) family file.

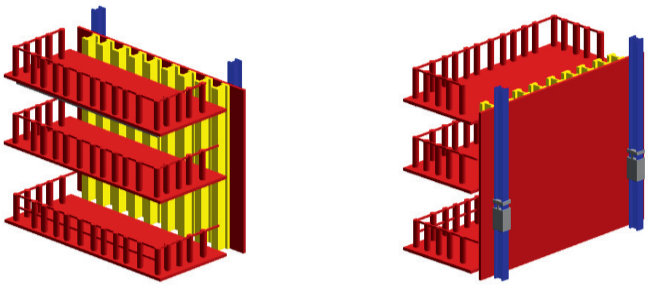


Fig. 10. 3D BIM automatic climbing formwork system (crane-independent system) family file.

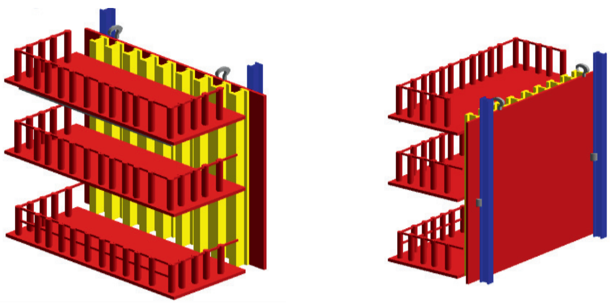


Fig. 11. 3D BIM semi-automatic climbing formwork system family file.

To incorporate 3D BIM climbing formwork systems family files in the 3D BIM Model, the procedures adopted are as follows.

- Conversion of solid 3D BIM Model into wireframe model [6], which acts as a reference for formwork family insertion [8].
- The conventional formwork family files created are loaded into the project, i.e., the wireframe model as in Fig 8., and the constructability assessment is carried out.
- Similarly the created 3D BIM Climbing Formwork family files as in Fig 9-10., are loaded in the existing project by deleting the already available 3D wall formwork family files.
- The above technique is repeated for other climbing formwork systems such as Automatic climbing formwork systems and Semi-automatic climbing formwork systems as in Fig 12., to perform constructability assessment.

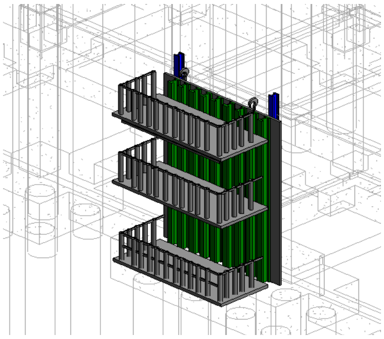


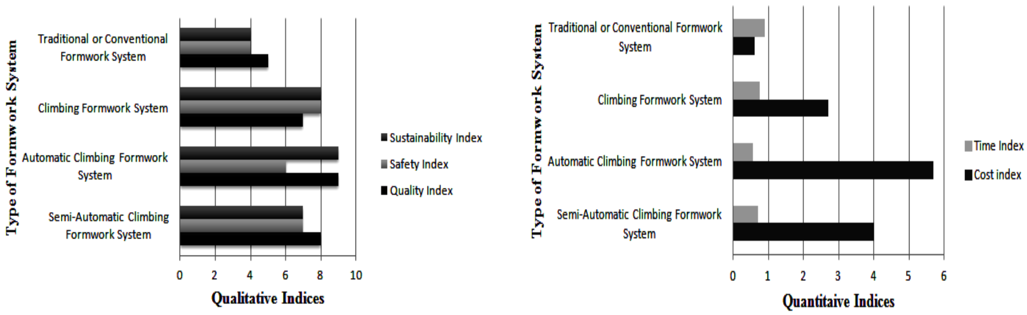
Fig. 12. Importing Automatic Climbing formwork System family file into the 3D BIM

## 4. Results and Discussion

The factors which influence the selection and operation of different formwork systems for the construction of core wall of high-rise buildings obtained from the constructability survey are given in Tab 2.

### 4.1. Quantitative and Qualitative Indices of Climbing Formwork Systems

From the Tab 2., the climbing formwork systems have additional advantages over the conventional wall formwork. However, a rational comparison was done between the conventional formwork and different climbing formwork systems as in Fig 13., so as to explore further significances of the climbing formwork systems.




(a) (b)

Fig. 13. (a) Qualitative Index; (b) Quantitative Index of conventional and climbing formwork system for core-wall construction.

## 5. Conclusion

From the Fig 13., we infer that Automatic climbing formwork systems may have additional advantages over other systems in-terms of quality and sustainability, it has considerably less safety aspect than the crane-dependent: climbing

Table 2. Factors influencing the selection and operation of traditional/conventional formwork systems and different climbing formwork systems.

| S.No | Criteria | | Conventional Formwork Systems | Climbing Formwork Systems | Automatic Climbing Formwork Systems | Semi-Automatic Climbing Formwork Systems |
|---|---|---|---|---|---|---|
| | Selection of formwork | | | | | |
| 1. | Building parameters | Height | Maximum 100 m | Minimum 75 m no maximum limit | Minimum 225 m | Minimum 125 m |
| 2. | -do- | Area | Maximum of 600 $m^2$/floor | Not an influencing factor | | |
| 3. | -do- | No.of stories | Upto 30 floor. | 40 floors and above | | |
| 4. | -do- | Type of high -rise structure | Rigid Frame System. | Framed wall system. | Framed tube system. | Framed Tube-in -tube system |
| 5. | -do- | Workspace | For making panels | Not an influencing factor | | |
| 6. | Construction Parameters | Type of projects | Not an influencing factor | Medium | Complex | |
| 7. | -do- | Construction Sequence | Wall casted ahead of beams and slabs | Monolithic Casting of Wall, long column, etc. | | |
| 8. | -do- | No. of reuse | Less than 5 | 15-30 | 40-50 | 30-40 |
| 9. | -do- | Rework | Lot of reworks | No problem of misalignment | | |
| 10. | -do- | Concrete Finish | Rough finish, needs plaster, improper corners and edges | High quality finish, the finish can also be enhanced by the use of formliners | | |
| 11. | Cost | Material | High | Medium | Low | Medium |
| 12. | -do- | Fabrication | High | Less, Prefabricated (only assembly) | | |
| 13. | -do- | Storage | High | Less, ready to fix and no storage | | |
| 14. | -do- | Transport | Less | High, requires since it is factory built | | |
| 15. | -do | Labour | Labour intensive | Low (only 8 to 12 people/panel) | | |
| | Operation of formwork | | | | | |
| 16. | Design Parameters | Type of Concrete | RMC is preferred. | Fluid concrete, SCC is extensively used in formwork | | |
| 17. | -do- | Rate of Pour | 40 $kN/m^2$ (max) | 90$kN/m^2$ (max) | | |
| 18. | -do- | Temperature | Only for hot weather concreting | Can also be used for cold weather concreting with provision for insulation or heating metal pipes | | |
| 19. | -do- | Cycle time | 1 floor/week | 1 floor/4-5 days | 1 floor/3-4 days | 1 floor/3-4 days |
| 20. | -do- | Form type | Gang Formwork | Rail Climbing Formwork System | | |
| 21. | Supporting Equipments | Crane | Crane-Dependent | | Crane Independent | Both |
| 22. | -do- | Platform | Need Scaffolding. | Platform with formwork itself | | |
| 23. | Site Parameters | Storage Yard | Required | Not an influencing factor | | |
| 24. | -do- | Safety | Poor Condition | High (Comfortable working area) | | |
| 25. | -do- | Accessibility | Required Higher | Operated even in narrow space | | |

formwork systems, semi-automated formwork systems. Thus, automated formwork systems are not advisable in the construction site located in the congested area, project with lack of technical sound work crew, and so on. However, if the conditions prove to be favourable for this system, it yields high time saving and would increase the profitability of the concrete formwork construction.

From this research the climbing formwork system proves to be very effective over conventional formwork on the factors like cost, time, quality, safety and sustainability. The adaptability of different formwork systems over the complexity factors associated with the construction of high-rise buildings is highlighted in Fig 14.

### 5.1. Further Research

The 3D BIM model of structural components considered in this paper is a generalized model however for advanced research on formwork systems; more complex 3D BIM models are developed for studying additional parameters. The formwork systems presented in this paper are custom made for the purpose of this research and it is more simplified

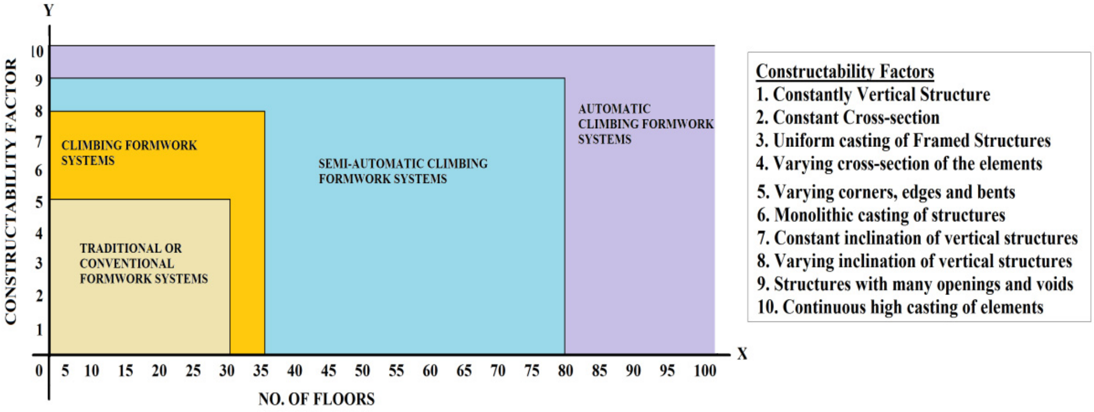



Fig. 14. Constructability factor of conventional and climbing formwork system for core-wall construction

Systems, thus for a detailed study on the actual formwork systems, the readers are advised to incorporate the available patented formwork systems in the BIM. The importance of climbing formwork systems are brought down only with the construction of core wall of high-rise building in this paper. Thus, the climbing formwork system shall be applied to other complex and advanced structures such as tall chimney, silos, pylon, etc., for illustrating further importance of this system. The comparison of climbing formwork system over conventional formwork system made in this paper can be well established by conducting Constructability/Buildability factors.

The other types of formwork systems such as Modular formwork system and other movable type of formwork systems can also be incorporated into the BIM for the constructability analysis. Besides the formwork, the falsework associated with the construction of formwork such as scaffolding, shoring and other formwork accessories [7] can also be incorporated to study the temporary structures of the construction as a whole.

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