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Automated Building Code Compliance for Structural Safety

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ABSTRACT

Safety in built environment is one of the top responsibilities and priorities of Governments of all countries. For this, Governments develop building codes. Checking for compliance of building codes is a tedious work in building design due to large number of complex codes containing hierarchical subdivisions and cross references. Technical developments in Building Information Modeling provide the prospective of automating this code compliance process and thus improving the effectiveness of building design and execution. This paper aims to provide a new automated framework for compliance checking process in building design, with respect to structural safety aspect of Reinforced Concrete Commercial Buildings. The reports generated were validated in terms of recall and precision.
Keywords: BFS, Building Information Modeling, Building Codes, CAD, Industry Foundation Classes, IS-456, RCC

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INTRODUCTION

Approval of the building designs by governing bodies is the mandatory task in every country before actual construction work can begin. Such approvals are done by checking whether designs comply with the building codes or not. The purpose of having building codes "is to establish the minimum requirements to safeguard the public health, safety and general welfare through structural strength, means of egress facilities, stability, sanitation, adequate light and ventilation, energy conservation, and safety to life and property from fire and other hazards attributed to the built environment and to provide safety to fire fighters and emergency responders during emergency operations" [1]. Building codes are developed by respective authorities and may vary widely from one country to another. Code compliance through manual process is a time-consuming and error prone task as there exist large numbers of codes which further contains referencing between clauses. The building codes don't contain any illustrations for helping designers envision the description in the text. Automation in code compliance can lessen the discrepancies caused by manual checking. It can provide the administrative bodies a consistent and uniform framework to check the compliances.

In order to process constraints, a digital representation of the product being designed is required. Earlier automated code compliance efforts were based on CAD (Computer aided Design). CAD provides the technical drawings which contain low level information about a building design. CAD doesn't provide the high-level information needed for code compliance applications. In the case of AEC design processes, Building Information Models (BIM), form a suitable representation [2]. These models not only get the three-dimensional geometry of the building, but the semantics of the individual elements also in the form of objects [3]. The National BIM Standard Project Committee defines a Building Information Model as a digital representation of physical and functional features of a facility and a shared knowledge resource for information about a facility [4]. As BIM provides a virtual construction of a building, it helps in identifying interference and construction related problems before they emerge and thus saves project costs and delays. This research paper aims to develop an automated code compliance checking system for checking building models against Building Codes with respect to structural safety aspect of Reinforced Concrete Commercial Buildings with National Building Codes of India [5] as an example. The development of a code compliance tool for a country can be considered as an e-governance tool which has potential to provide better service delivery at reduced costs, increase public sector efficiency. It also aims to provide an open environment for writing rules.

RELATED WORK

Researches regarding computerisation of rules and building codes and standard checking have been initiated since the mid-sixties. One of the most significant studies is done by [6] who explored use of decision tables to represent AISC standard specifications. According to Fenves, automating the process of building code compliance is a complex and challengeable task to perform in computer-aided building design, due to complex nature of codes and inadequate representation of models for code checking.

Many efforts and attempts from research groups, trade associations, and software developers world-wide have been made to address these challenges in computer-aided building code compliance checking for the last two decades. An integrated hypertext and knowledge-based computer tool has been developed [7] to assist code compliance checking called HASES (Health and Safety Expert System) that focused on occupancy and code hazards in National Building Code of Canada. An integrated client/server framework for compliance checking of a design against a building code for disabled accessibility is demonstrated [8].

Many research approaches used object oriented representation of buildings and codes for checking process. A prototype system for automated building code checking has been developed [9] where both building designs and building codes are represented using OO (object-oriented) model. An object-based building modeling approach was followed [10] for representing both building designs and building codes to facilitate the automated online code-checking process in a distributed environment. An object based interpretation of rules is done for code checking [11].

Research efforts are done world-wide to automate rule checking in buildings with IFC building models as input [3]. These are the Singapore CORENET project, the HITOS project by Norwegian Statsbygg, the effort by the Australian Building Codes Board, the International Code Council in the US and the General Services Administration effort. [12] reviewed previous research into automated code compliance and identified the key requirements for automated code checking. Various issues for integrating building codes in CAD are examined by [13]. A framework for Automated Code Compliance Checking for Building Envelope Design is provided by [14]. [15] compared strengths and weaknesses of major compliance checking tools and also examined the applicability of these tools for fire safety clauses of New Zealand code. A Model View Checker is developed [16] on top of the Bimserver.org framework for IFC models based on mvdXML format for structuring rules.

IFC has many limitations such as limited expression range, difficulties in partitioning the information and the possibility of describing the same information in various ways [17]. These limitations can be improved by deploying semantic web languages. [18] used concepts of ontology to convert BIM into a construction-specific feature-based model (FBM). A rule based semantic approach is proposed by [19] that addresses the complexities in the regulations. A semantic concept of RASE is used [20] for transforming codes documents into rules for checking on a BIM software. [21] used the concept of graphs for representing rules from various building codes.

This section has reviewed the various efforts done in the field of compliance checking. Most of these research efforts are location specific, as each country/region has its own regulations and these changes periodically. So it is difficult to use software for automated building code checking for one country for checking building codes of another country. Another problem is, there are difficulties in adding new codes in an existing rule set of items which requires accessing the API (Application Programming Interface) for additional programming. Research is still needed to develop the object-based, more efficient, sharable and standardised and open source representations for both code provisions and building designs. This research aims to develop an e-governance tool for code checking.

RESEARCH METHODOLOGY

The research methodology adopted is as follows:

- Study the Building Codes and represent them in process ready format as per the automation software requirement.
- Plan, execute and build data base building models for representing the models in IFC and map them to Structural Codes (IS-456 as example).
- Develop an automation compliance checking Script and framework for checking Safety conformance.
- Evaluate the automation framework for its accuracy with the help of human subjects' experts.

IMPLEMENTATION OF THE MODEL

Building Information Modeling is essentially a digital format for representing the physical and functional attributes, properties of building units with which the physical structure is made up of. It allows multiple ways in which the physical structure model can be shared in multiple domains. The sharable model is represented in IFC standard, which is an open source standard.

The IFC (Industry Foundation Classes) file may be of text format (ISO 10303-21), XML format (ISO 10303-28) or Zip format (zipped IFC-SPF file) as per the requirement. By definition, IFC is an ISO standard for interoperability, specified and developed by BuildingSMART that provides exchange of information throughout the project lifecycle. The IFC standard represent the geometry and properties of building objects and their relationships within building elements, thus assists in organisation of information across incompatible applications [22] as required by BIM models. The IFC-SPF format is available in IFC 2X2, IFC 2X3 and IFC 4 versions. However, the model implemented in this proposed system works with IFC 4 format.

IFC files contain the building meta-data which needs to be extracted for developing applications. Attributes such as volume, length of a building element are directly available but some information is not available and has to be computed. e.g. if rebars are placed in a column, spacing has to be calculated from the coordinates information, given by IfcCartesianPoints. There is plethora of IFC file parsing application in market, but few initiatives in open source domain which have limited scope for checking code compliance [23].

The research work carried out in the current context can be understood using layered approach. Figure 1 gives a view of the various layers of the said system.

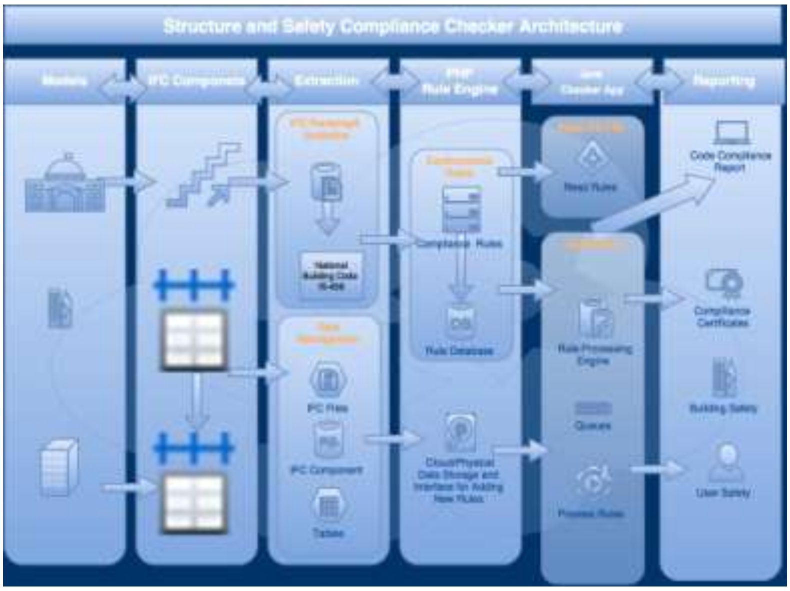

Figure 1.Structure and Safety Compliance Checker System Architecture

The purpose of adopting layered approach is that compliance application will be scalable, easy to maintain and will have reusable components. In addition, the application will support high degree of integration and interoperability with third party or allow extension of compliance system. The solution is designed with separation of components having cohesive similar abstraction levels. The lowest level abstraction is the Layer 1. It forms the basis of the system and successive layers add more functionality interactively.

Layer 1: In this layer, the physical building models are planned, designed and built using BIM software. There exists various BIM software like Revit, Tekla, ArchiCad, FreeCAD etc. In this context, Revit [24] is used for creating IFC representation of physical building models. Various test cases are generated based on different models with varying complexity. Here model of a shed is used as a reference as shown in Figure 2.

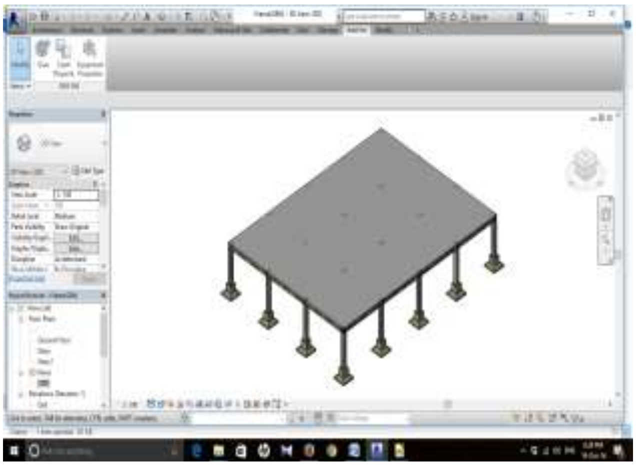

Figure 2.Model of a Shed in Revit

The focus of this paper is checking RCC structural codes. So the reference model contains various structural elements like columns, beams, slabs, footings etc. that are further reinforced. In order to check the physical building design conformance, the dimensions of various building elements in the model need to be checked.
Layer 2: IFC is used to retrieve building model data needed for code checking. A BIM model created using Revit is exported in an IFC 4 format which is the latest format of IFC, released in 2013. IFC4 includes enhancements of geometry and parametric features, and has support for product libraries [25]. There are various commercial as well as open source IFC viewers available to view IFC files such as Solibri Model Viewer, DDS CAD Viewer, Constructivity, BIM Vision etc. But most of these support IFC2x3 format of IFC. In this research work, a Java Application, based on IFC Java Toolbox library [26] is built to view and extract data from models built in IFC 4 version. The extracted model data then works with rule engine for compliance checking. Java 8 is used for application development.

Layer 3: The IFC file generated from a building model is parsed at this layer. The IFC file, when parsed, gives meta information on the various components of the building such as stairs, footings, columns etc. The information of each component needs to be semantically mapped with National Codes. This layer extracts properties of structural elements which are to be checked according to particular IS-456 clauses in National Building Code of India.
IFC entities contain references to each other as shown in Figure 3.

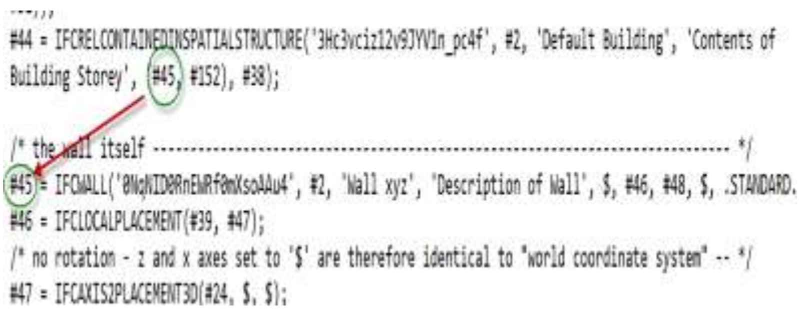

Figure 3.IFC sample file

Here IfcRelContainedInSpatialStructure, is used to assign elements to a certain level of the spatial project structure. Ifcwall contains reference to object placement (IfcLocalPlacement) and product representation (IfcProductRepresentation). The IfcLocalPlacement defines the relative placement of a product in relation to the placement of another product or the absolute placement of a product within the geometric representation context of the project. It contains further reference to attributes PlacementRelTo and RelativePlacement.
The structure of IFC4 specifications is designed as a hierarchal structure. For reading and extending the hierarchal structure, IFC data model is implemented as a Graph structure based on Graph Theory. Here nodes represent Ifc entities that start with "#" and edges represent the reference from one entity to another. To get the values of these attributes and properties, we need to traverse through the structure using an algorithm. Queue data structure is used to store the entities and referred entities which are then traversed using BFS (Breadth First Search) approach where referred entities are considered as adjacent nodes. The algorithm work on the model by iterating through IFC data instances as nodes of the graph structure.
Figure 4 shows the extraction of the IFC element attributes from an IFC file.

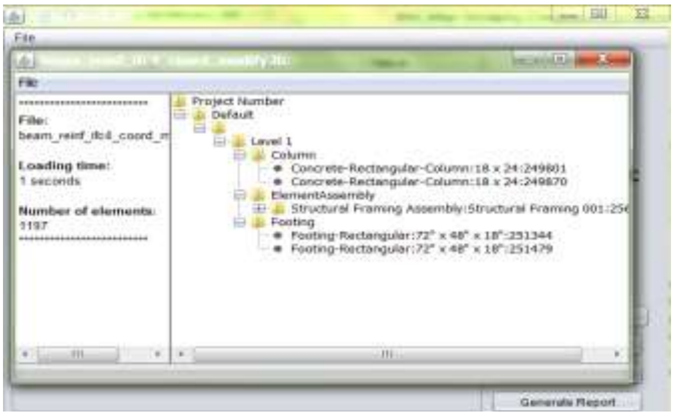

Figure 4.Output of the IFC file Traversal Application

Layer 4: This layer mainly deals with the rules database. Compliance checker systems maps the IFC components Meta information like length, width, cross sectional, gross sectional area with IS 456 codes standards. The system is pre–fed by using the concept of master tables and transactional tables. The IFC standard hierarchy of components is pre-fed and mapping occurs as the file is parsed. The system maps the input variables and output variables of both the standards. Figure 5 shows the rule engine with sample rule base from IS-456.

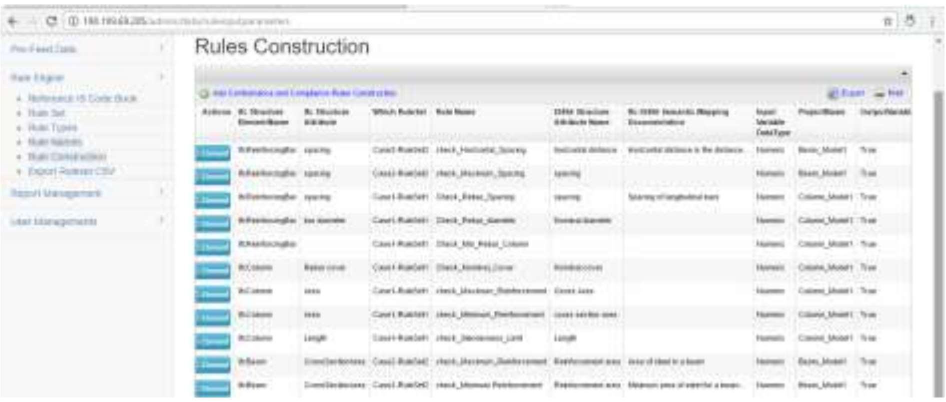

Figure 5.Rule Engine

Layer 5: In this layer, code compliance is done. The cloud based system provides an interface to make rules. Each rule has input, processing and output parts. The input part stores information on the input factors or variables required to run the rule expression. The rule expression is mathematical form of the check, which need to be applied for conforming to government standards. The output variables are the variables that represent the result as conformance or nonconformance or non-conclusive. The processing part consists of the mathematical expression having arithmetic operator. The mathematical operator represents a greater to, less than (maximum and minimum) conditions of the rule. Table 1 shows the partial list of rules applied for a beam.

Table 1. Beam Codes IS-456

S. No.	Checks	Formula/ Value	Code	Clause	Notation
1.	Slenderness Limits				
a	A simply supported or continuous beam shall be so proportional that the clear distance between the lateral restraints does not exceeds	60b or 250b²/d whichever is less	IS-456	23.3	d= effective depth b=breadth
b	For a cantilever, the clear distance from the free end of the cantilever to the lateral restraint shall not exceed	25b or 100b²/d	IS-456	23.3	d= effective depth b=breadth
2.	Minimum Reinforcement	As=0.85bd/fy	IS-456	26.5.1.1	As= Minimum area of tension reinforcment , b = breadth of beam, d= effective depth, fy= characteristic strength of reinforcement N/mm²
3.	Maximum Reinforcement	Not greater than 0.04bD	IS-456	26.5.1.2	b=breadth of beam D= overall depth

Table 2 shows the semantic mapping of IS-456, Limit theory mathematical expression to the IFC standard. The formula is broken into IFC structure elements' dimensions as input variable and expected output.

Table 2. Example of Semantic Mapping of the IFC to IS-456

S. No.	Rule	RuleSet	IfcStructure	Mathematical Expression	Input	Output	Constant	Operator
1	Beam Deflection	Ruleset 1	ifcBeam	bD<L/20	ifcLength	True/False	20	Greater than
2	Minimum Reinforcement	Ruleset2	ifcColumn	As>.008*Gross Area	Area	True/False		Greater than
3	Maximum Reinforcement	Ruleset2	ifcColumn	As<.04*Gross Area	Area	True/False		Less than

Layer 6: Once the semantic mapping of the checks is complete and fed into the system, the system can be used for running full scan for compliance checking. This step finally generates compliance reports after importing the ruleset and then processing the IFC file and ruleset file. An HTML report is generated which gives results that whether a particular rule for a specific element is valid or not. Figure 6 shows a sample conformance report.

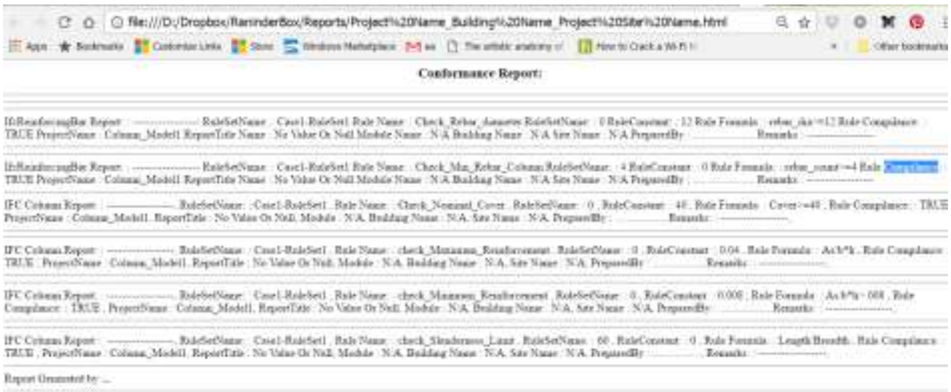

Figure 6: HTML Code compliance Report

I. RESULTS AND DISCUSSION

In this research work, structural codes IS-456 compliance is checked by building custom rule sets per ifc model. The application works for reinforced columns, beams, slabs, footings elements. All these codes are translated into rule expression (mathematical) and entered into the rules database. A Java application extracts data from ifc model files and works with a rule engine to generate html formatted reports.

To check the accuracy of the reports, human subjects were engaged and output of 21 reports was examined. The examination process used the random sampling method to design the experiments (DoE) and investigate the level of accuracy of compliance system. Out of full set of 21 reports, random sets of compliance reports were created with maximum of 5 reports and minimum of 2 reports. These sets were sent to the experts for evaluation of their correctness. The experts checked the contents and outcomes of the rules compliance for each set of reports and gave score. The computation of the score was based on frequency of the valid rules created and number of rules accurately processed. To maintain the inter-rater reliability and for removing conflicts, the percentage of agreement was computed. It was found that in only 2-3 cases the disagreement distance was more than 0.5, which reflects that most of the judgments by human experts seem to be similar. The original contributions done so far by undertaking this research work is structural safety and conformance rule building engine with cloud support.

CONCLUSIONS AND FUTURE WORK

If the buildings, all over the world, need to be of global standards and the manpower needs to be equipped with latest technologies in constructions, we need to follow globally recognized standards like IFC. This paper presented a framework for automated code compliance considering Indian National codes as example. In developing countries, use of BIM has just started. Its full adoption has a long way to go. Examining the advantages of BIM, it is time to use it for code checking as well. After conducting systematic literature survey on the safety and compliance, it was found that only few commercial checkers are available and also these are specific to their respective countries. Hence, there is need to build such systems that can take advantage of BIM for code compliance and can help governments as an e-governance tool. The proposed work is limited to the module of safety and structure. For future directions, it is suggested that other modules may be incorporated such as HVAC Controls, Facilities Management, Construction, Electrical, Building controls. The current system is extendable for these modules.

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