PACE-2021
International Congress on the Phenomenological Aspects of Civil Engineering

Research Article 20-23 June 2021

Investigating Facade Performance for Climate Responsiveness in India

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Keywords

Building facade,
Glazing, solar load, daylighting,
Facade performance, Simulation.

Abstract

The buildings in the present scenario are consuming a lot of energy through electrical and mechanical means to provide thermal comfort. The building façade plays an important role in the whole building's energy performance. The energy demand is led by heating and cooling and artificial lighting. This research aims to examine the performance of various strategies on the building's facade to limit solar radiation and reduce cooling loads by different facade materials application. Four different modules, having different facade material applications are hypothetically assumed in Indian climatic condition, for the purpose of the study. The design strategies considered are; material properties, openings, and daylight, solar loads, percentage of glazing factors. This research applies the simulation method using Autodesk Revit with plugin FenestraPro, to investigate various building model's implications to calculate three building factors; glazing, solar loads and daylighting. Simulation is done to explore better performative building's facade and achieve the best possible outcome. A comparative analysis of all four modules based on facade performance, solar load, daylighting, and annual average solar radiation received by facades is presented as an aid for decision making regarding facade selection.

1. Introduction

The world today is facing problems of global warming and climate change. Without exception, the buildings in India contribute up to 30% of global annual greenhouse gas emissions and consumes up to 40% of all energy [15]. Building facade acts as a barrier layer between the outdoor environment and the internal of a building and block the external environmental effects and maintain the internal environment condition with minimum energy consumption and reduce the annual expenditure on electrical and mechanical consumptions and maintenance. The modern building design depends more on a mechanically controlled environment to maintain the comfort of occupants, thereby increasing energy consumption.

The building facade is one of the most significant contributors to the energy consumption and comfort parameters of any building. Building facade controls many physical external as well as internal environmental factors like heat, light, sound, weather conditions. Hence, it is an essential part that needs consideration during the design process. Building facades need to perform well in order to block the external environmental effects, maintain internal thermal comfort, reduce the energy consumption, and maintain the overall thermal comfort of users.

The External skin of a building corresponds to the architecture response i.e., style, identity, and allots character to a building. Moderator between internal and external environments are categorized as [7]

a) Weathering
b) Security
c) Energy Performance

This research aims to analyze the performance of different facade materials to control or minimize thermal heat gain by building through building facades. This study shall help to reduce heat gain by careful selection of facade materials.

2. Functions of facade

Facade plays an important role in the performance of any building like, bearing different loads and performing various tasks at the same time. Facade presents the building aesthetically as well gives it stable appearance in any condition. The facades of a building create a barrier between internal space and outside climate conditions to maintain the building's internal temperature.

There are various performance factors related to design of building facades that play an important role in the decision regarding the selection of suitable materials to be used in the design of a building facade [12.]

The different factors which are considered while selecting the facade material in buildings are:

Durability

The facade of a building should be durable and capable of resisting any type of harsh condition. It is a very important that the material of a facade should be durable, capable to hold, and perform various essential functions. The life span of facade material should be same as the life span of a building and it should not require to be changed or restored by new facade material [13].

Facade material tolerates various aggression that may be manmade (like industrial pollution) or natural weather conditions (sun, rain, snow, etc.) and hazards. In all these conditions, the facade material should be strong enough to face challenges from cracking, punches, holes, scratches, deteriorating.

Thermal performance

A crucial consideration is the facade's thermal performance. Thermodynamic qualities of building facades are linked to a specific location and materials, as well as material design and qualities [8].

During summers, the increase in temperature and high solar intensive heat exposes the building facades to higher thermal heat gain in the buildings.

Minimizing energy and enhancing the facades' thermal performance helps to reduce the energy consumption of a building. It provides the thermal comfort, better thermal resistance, and improves the building system to reduce the building cooling cost [4].

Functional performance

Functional performance is the operative performance of materials and includes the capability of material to be repaired easily, within minimum time, and also reduced the cost of maintenance [15]. Functional performance of facade material is important to check the materials for the best capability outcome with the least flaws. It is important to list down a record of various material performances and choose appropriately so as to avoid using materials that have high thermal heat gain capacity [2].

Weather resistance

Facade material should be weather resistant and act as a building envelope that protects the building from various weather exposures. It should also prevent unwanted sound produced by air pressure on the surface of the facade i.e. air infiltration and exfiltration, should be capable of blocking the seepage of water, and prevent unwanted bacteria and insects' growth.

Cleaning performance

The cleaning performance of materials is required for an aesthetical and functional purpose, and it is the capability of material to be cleaned easily [3].

The cleaning performance is a measure that emphasizes on different type of materials maintenance and cleaning rate, and the techniques of cleaning and maintenance, those are required to give long life span and keep the building protective [16].

Acoustical performance

Nowadays, acoustic control is an important part of designing building envelopes. In urban areas, noise pollution by road traffic and traffic flow is a major issue and acoustically resistant building envelope is required [8].

While designing facades, the materials should not be creating self-generated noises, such as those produced by wind movement and internal or external aggressive forces [9].

Health and safety

Two main important aspects are health and safety in counting and rating facade material parameters while selecting the material for facades [6].

At present, the buildings materials contain chemicals as well as harmful metals that may affect human health in terms of breathing problems, headaches, irritation, etc., and several other related problems. Britain Research observes that indoor air relative humidity should be 40% and 60% for human health and this range is most appropriate. The relative humidity of the air humidity is lower than 40%, it is measured as 'sick buildings' [7].

Maintenance

Low maintenance requirement of building material will increase the building lifespan and also increase the building function. Simultaneously, maintenance also reduces the future cost of repairing, fixing, and replacement work [6]. Therefore, better maintenance of the building reduces the cost of maintenance of the building [10].

Daylighting

Designing of building facade includes the daylight factor that is very important for considering and visual comfort. While designing any space or building the designers should consider the illumination levels, daylight factor distribution, and also protection from the direct sunlight and glare, and allow more diffuse light that is good for interior spaces. Combination of various building systems is also a very important part of any building design. In facade design, its role as protecting shield, artificial and natural lighting, shading devices, HVAC systems, and building functionality need to be controlled together to act as an Energy Efficient Building [1].

The building orientation and Window to wall ratio (WWR) of a building provides the natural light for interior spaces. The basic use of daylighting is to provide better natural daylight deep inside the building spaces and the conservation of energy use. Some translucent glazing facade materials provide the filtered and uniform glare-free daylighting inside the interior spaces and provide good ambiance [14].

3. Characteristics and properties of facades

a) Allowing daylight into a building through the facade
b) Preventing the building from extreme direct solar heat gain
c) Wall mass store the heat
d) Improve the insulation property of a material to prevent the heat transfer from outside to inside building
e) Facade material should be air or moisture-resistant to prevent it from penetrating inside the building
f) Building facade should also allow to cool down the interior spaces of the building by natural ventilation [11]

The above properties are extremely dependent on the type of climate, as well as they also depend on function of building, occupancy load of the building, the orientation of building, and the equipment loads like heating and cooling loads, as well as the type of facade and facade materials. On the basis of physical characteristics, there are two types of facades:

Opaque facades

These are the basic layers in the construction of a building built by solid material, such as masonry, brick, stone, cladding, precast concrete paneling, and insulation material. Opaque facades also include openings for windows and balcony, or any other openings.

Glazed facades

Glazed facades are glass paneling, curtain walls, or transparent or translucent facade glazing materials, which are mainly used for visibility and for maximizing daylighting in interior spaces of buildings [1].

The physical behaviors, properties, the construction methods or fixing of material are different for these two types of facades.

Opaque facades are usually more massive and bulkier and have greater insulation properties, and poor in solar heat transfer from outside to inside spaces as compared to glazed facades. On the other hand, the building's glazed facades are mainly allowing maximum natural daylight to the interior spaces, provide view to the users, are structurally lightweight, and impose less dead load on the building structure in comparison to the opaque facades [1].

4. Description of project

Building facades act as a barrier and help to reduce the building energy consumption, as they play an important role in controlling the solar heat gain from outside in a building. An attempt has been made in this study to examine the response of different facade materials in achieving maximum comfort and high performance.

The simulation is done on a hypothetical high-rise building located in Delhi, India. Delhi faces an extremely high-temperature climate, and many high-rise buildings take an extra cooling load to provide thermal comfort inside the building. Climate responsive facade may help reduce the cooling energy load consumption inside the building with the help of facade.

a) Per floor area : 26895 ft^2
b) Total floor area : 564815 ft^2
c) Total facade area: 165311 ft^2
d) Number of stories: G+20
e) Floor to floor height: 12 ft.
f) Total building height: 252 ft.

Following assumptions were made to analyze the thermal behavior of facade throughout the year. Hypothetical high-rise office building with G+20 floors, building occupancy pattern: from 7:30 am to 18:00(6:pm), building simulation months in use from 01 January 2021 to 31 December 2021.

About simulation software

The simulation of the building facade is done on FenestraPro for Revit with Autodesk Insight plug-in for Revit as this tool considers the environmental factors on facades and buildings. This software gives a more accurate result, gets more glazing specifications, and provides more detailed results of the simulation. In this software there are different material libraries with updated new building facade materials and also specifies it with region type. In this experiment, Delhi comes under Asia, the Asian material library is selected.

FenestraPro mainly calculates three-building factors [7]:

a) Glazing
b) Solar loads
c) Daylighting

Simulation of high rise building of the thermal facade's behavior

The building energy model is used for building facade material analysis by fixing facade glazing as 95%, and the building orientation. The methodology included creating four modules of the model using four different types of facades glazing material to analyze the different materials and examine how much building facades receive solar heat, and calculate the facade performance.

The study aims to analyze the four different types of glazing specification building facade materials, facade performance, U-value of material. It will measure the material insulator property (lower the U-value more is the insulator), amount of solar load, and daylighting inside the building. The higher the R-value better is the insulation of material.

5. Results and Discussion

Simulation is done on four different types of building facade material to compare modules and examine heat transmission by the facades, such as 95% building façade glazing, double glazing, daylight factor. Fully glazed facades are widely used nowadays as they reduce the dead load of building. The conceptual mass model is considering 95% glazing and 5% frame and mullions, hence it is using 95% glazing to simulate and analyze the maximum output of the facades.

Table 1. Comparative analysis of specification of module 1, module2, module3, and module 4

S.no.		MODULE-1	MODULE-2	MODULE-3	MODULE-4
1.	Glazing specification material	Double glazing domestic SC=0.4	6mm Optiblue,1/2" Air, 6mm Solarbar 67(3)	SunGuard, DS Bronze 30/23 Double glaze	Double Low-E (argon) with ext. woven shade.
2.	Façade performance	3.3sq.ft Fhr/ BTU	3.7sq.ftFhr/ BTU	3.7sq.ftFhr/ BTU	3.3sq.ftFhr/ BTU
3.	U value of glazing BTU/(sqft.Fhr)	0.32	0.28	0.28	0.32
4.	Glazing	95%	95%	95%	95%
5.	R- Value	1.9 sqft.hr/ BTU	3.59 sqft.hr/BTU	3.49 sqft.hr/BTU	5.62 sqft.hr/BTU
6.	Solar Loads	15.03 BTU/sq ft. Hr (Too high)	13.9 BTU/sqft. Hr (Too high)	8.08 BTU/sqft. Hr (Too high)	2.69 BTU/sqft. Hr (Too low)
7.	Daylighting	6.6%	4.37	3.36	0.78 (too low)

Module-1

The first module presented in Table 1 means the facade material is double glazing domestic SC=0.4, U-value of glazing is 0.32 BTU/(sqft. Fhr), R-value 1.9 sqft.hr/BTU, solar loads on building facades 15.03 BTU/sqft.Hr(Too high), Daylighting received by internal space is 6.6%, overall facade performance of the module-1 building is 3.3sq.ftFhr/BTU.

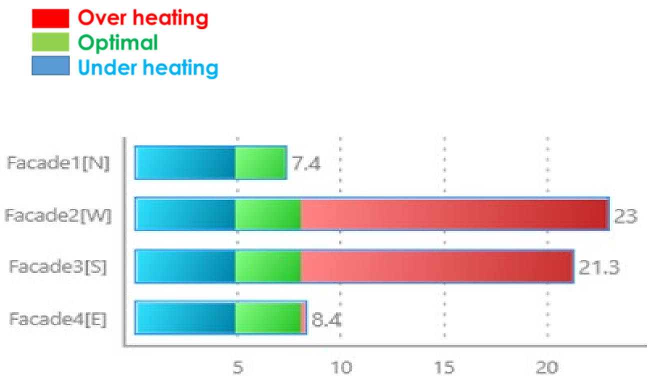


Figure 1. Annual average solar heat in Module -1

Figure 1 represents that the building facades receive average solar heat throughout the year on each facade. The north facade received the minimum solar radiation and the west facade receives maximum heat throughout the year.

Table 2. Module-1, monthly and annual average solar loads per unit floor area within the perimeter zone per facade (BTU/sq.ft.)

	FAÇADE-1 (N)	FAÇADE-2 (W)	FAÇADE-3 (S)	FAÇADE-4 (E)
JAN	5.93	18.83	33.22	7.77
FEB	6.21	24.47	31.73	8.43
MAR	6.88	28.5	25.49	8.84
APR	7.89	26.12	17.82	9.32

MAY	9.19	25.55	11.86	9.26
JUN	9.54	22.13	9.38	8.97
JUL	8.31	17.24	8.81	8.21
AUG	8.27	18.77	11.86	8.84
SEP	7.45	24.82	18.8	8.65
OCT	6.72	24.25	28.94	8.02
NOV	5.85	24.31	33.06	6.82
DEC	5.1	22.38	35.38	6.63
ANNUAL AVERAGE	7.39	23.05	21.33	8.37

*solar load per unit floor area within the perimeter zone per facade (BTU/ft² hr)

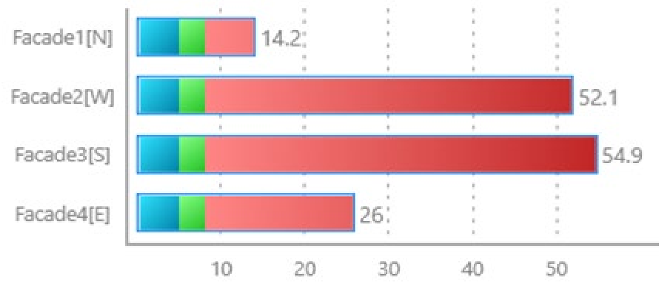


Figure 2. Module-1 building received peak solar heat.

Maximum solar heat is received by the south facade of the building (Figure 2).

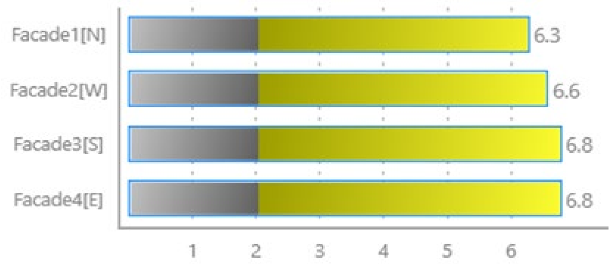


Figure 3. Module-1, Daylighting chart

According to figure 3, the module-1 daylight factor received by the different facades of a building can be analyzed as; maximum daylight is received by the south facade (6.8%), and east facade (6.8%) of building. East and south facades receive higher intensity of daylighting into the interior spaces. It will help to reduce the artificial lighting and electricity bills but solar radiation is much higher.

Table 2 and Figure 4 show the monthly amount of solar heat received by different facades of the building. Maximum solar radiation is received by the west facade in July.

Monthly and average annual solar radiation inside the building is shown in figure 4. Peak solar radiation is received by the building facades in May, June, and July.

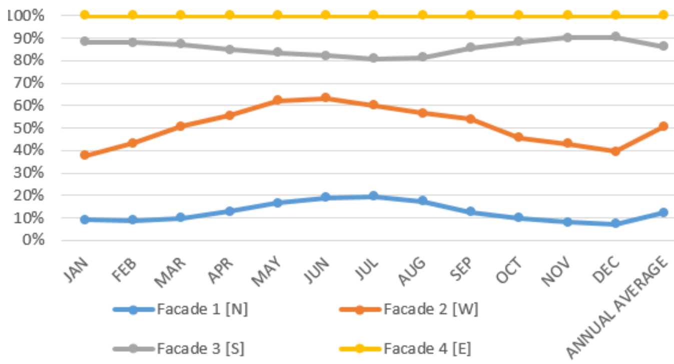


Figure 4. Monthly and annual solar load received by each facade of the building.

Module-2

In the second module, the façade material is double glazing 6mm Optiblue,1/2" Air, 6mm Solarbar 67(3), U-value of glazing is 0.28 BTU/(sqft. Fhr), R-value 3.59 sqft.hr/BTU, solar loads on building facades 13.9 BTU/sqft.Hr(Too high), Daylighting received by internal space is 4.37%, overall facade performance of the module-2 building is 3.7 sq. ft for/BTU (Table-1).

Table 3. Module-2, monthly and annual average solar loads per unit floor area within the perimeter zone per façade (BTU/sq.ft.)

	FACADE-1 (N)	FACADE-2 (W)	FACADE-3 (S)	FACADE-4 (E)
JAN	5.17	16.42	28.97	6.75
FEB	5.42	21.33	27.67	7.35
MAR	5.99	24.85	22.22	7.7
APR	6.88	22.79	15.53	8.12
MAY	8.02	22.28	10.33	8.05
JUN	8.31	19.27	8.18	7.8
JUL	7.26	15.03	7.7	7.16
AUG	7.2	16.36	10.33	7.7
SEP	6.5	21.65	16.39	7.54
OCT	5.83	21.14	25.23	6.97
NOV	4.88	21.21	28.82	5.96
DEC	4.47	20.07	30.84	5.77
ANNUAL AVERAGE	6.44	20.07	18.58	7.29

*solar load per unit floor area within the perimeter zone per façade (BTU/ft² hr)

Table 3 represents the monthly amount of solar heat received by the north, west, south, and east facades of the building. The maximum annual solar radiation is received by the west facade (20.07) and the minimum solar radiation received by the north facade i.e. 6.44.

Average solar heat received by building facades throughout the year on each facade is shown in Figure 5, where the north facade received the minimum solar radiation and maximum heat is received by the west facade throughout the year.

According to Figure 6, the building's peak solar radiation, maximum solar heat is received by the south facade of the building.

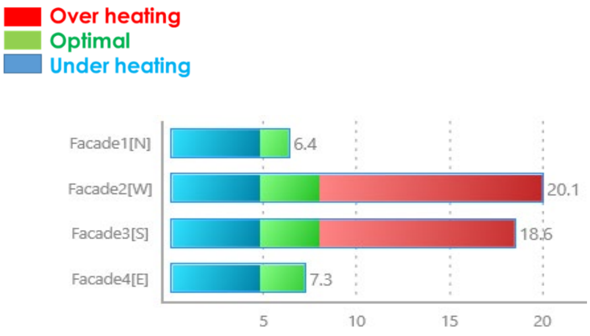


Figure 5. Annual average solar heat received by each facade in Module-2

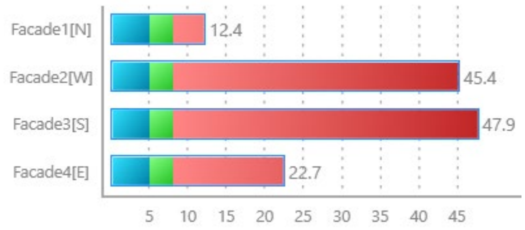


Figure 6. Peak solar heat received by building in Module-2

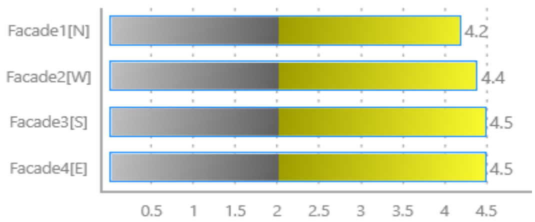


Figure 7. Daylight chart in Module-2

In figure 7, the module-2 daylight factor received by the different facades of a building are shown. Maximum daylight is received by south (4.5%) and east (4.5%) facades of a building, annual average daylight received is 4.37%. East and south facades received a higher intensity of daylighting into the interior spaces. It will help to reduce the artificial lighting and electricity bills but solar radiation is much higher.

Monthly amount of solar heat received by the different facades of the building is shown in Figure 8. Maximum solar radiation is received by the west facade in July.

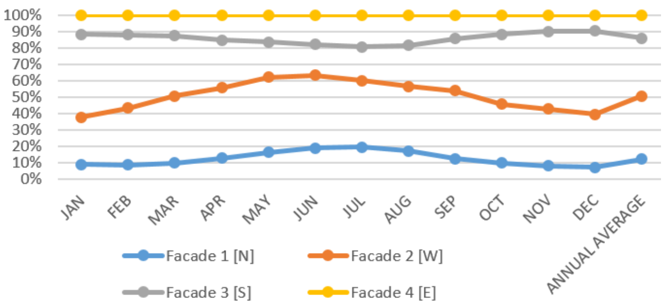


Figure 8. Monthly and annual solar load received by each facade of the building

Module-3

In table-1, for the third module the facade material is SunGuard, DS Bronze 30/23 Double glaze, U-value of glazing is 0.28 BTU/(sqft. Fhr), R-value 3.49 sqft.hr/BTU, solar loads on building facades 8.08 BTU/sqft.Hr(Too high), Daylighting received by internal space is 3.36%, overall façade performance of the module-3 building is 3.7 sq.ftFhr/BTU.

Table 4. Module-3, monthly and annual average solar loads per unit floor area within the perimeter zone per façade (BTU/sq.ft.)

	FACADE-1 (N)	FACADE-2 (W)	FACADE-3 (S)	FACADE-4 (E)
JAN	3.17	10.14	17.91	4.18
FEB	3.36	13.19	17.09	4.53
MAR	3.71	15.34	13.73	4.75
APR	4.25	14.07	9.61	5.01
MAY	4.95	13.76	6.37	4.98
JUN	5.14	11.92	5.04	4.82
JUL	4.47	9.29	4.75	4.44
AUG	4.44	10.11	6.4	4.75
SEP	3.99	13.38	10.11	4.66
OCT	3.61	13.06	15.56	4.31
NOV	3.01	13.09	17.82	3.68
DEC	2.76	12.05	19.05	3.58
ANNUAL AVERAGE	3.96	12.39	11.48	4.5

*Solar load per unit floor area within the perimeter zone per façade (btu/ft² hr)

The monthly amount of solar heat received by the north, west, south, and east facades of the building is shown in Table 4. The maximum solar radiation received annually by the west facade is 12.39(BTU/ft² hr) and the minimum solar radiation received by the north faade 3.96(BTU/ft² hr).

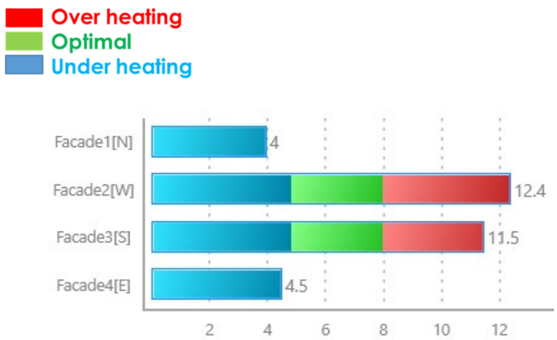


Figure 9. Annual average solar heat received by each facade in Module-3

Building facades receive average solar heat throughout the year on each facade, the north facade received the minimum solar radiation and maximum heat is received by the west facade throughout the year (Figure 9).

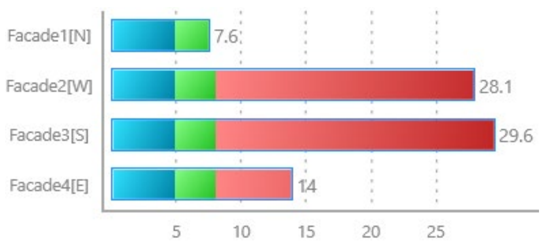


Figure 10. Peak solar heat received in Module-3

As shown in Figure-10, maximum solar heat is received by the south facade of the building, and minimum solar radiation is received by the north facade of the building.

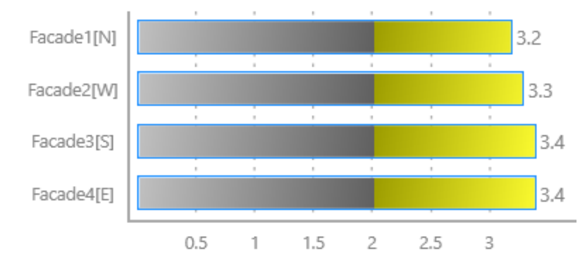


Figure 11. Module-3, daylighting chart

Daylight factor received by the different facades of a building for module-3 is shown in figure 11. Maximum daylight is received by the south (3.4%) and east (3.4%) facades of a building, annual average daylight received by 3.36%. East and south facades received a higher intensity of daylighting into the interior spaces. It will help to reduce the artificial lighting and electricity bills but solar radiation is much higher.

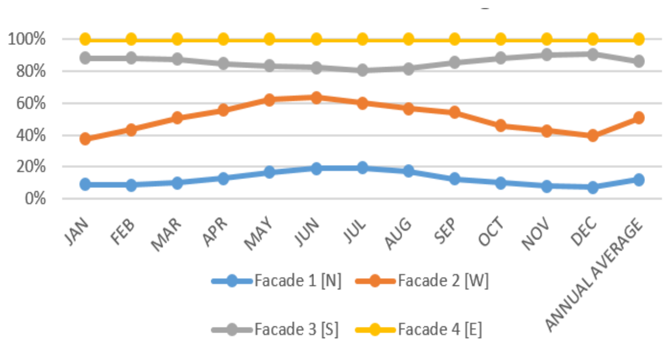


Figure 12. Monthly and annual solar load received by each facade of the building

In figure 12, the chart shows the monthly amount of solar heat received by the different facades of the building. Maximum solar radiation is received by the west facade in July.

Module-4

As shown in Table-1, for the fourth module, the facade material is Double Low-E (argon) with ext. woven shade, U-value of glazing is 0.32 BTU/(sqft. Fhr), R-value 5.62 sqft.hr/BTU, solar loads on building facades 2.69 BTU/sqft.Hr(Too low), Daylighting received by internal space is 0.78%, overall facade performance of the module-4 building is 3.3 sq.ftFhr/BTU.

The monthly amount of solar heat received by the north, west, south, and east facades of the building is shown in Table 5. Maximum solar radiation received by the west facade in July is 9.29(BTU/ft² hr) and minimum solar radiation received by north façade is 3.96(BTU/ft² hr).

Table 5. Module-4, monthly and annual average solar loads per unit floor area within the perimeter zone per façade (BTU/sq.ft.)

	FAÇADE-1 (N)	FAÇADE-2 (W)	FAÇADE-3 (S)	FAÇADE-4 (E)
JAN	1.05	3.39	5.96	1.39
FEB	1.11	4.41	5.71	1.52
MAR	1.24	5.1	4.56	1.58
APR	1.43	4.69	3.2	1.68
MAY	1.65	4.6	2.12	1.65
JUN	1.71	3.96	1.68	1.62
JUL	1.49	3.11	1.58	1.49
AUG	1.49	3.36	2.12	1.58
SEP	1.33	4.47	3.36	1.55
OCT	1.2	4.34	5.2	1.43
NOV	1.01	4.37	5.93	1.24
DEC	0.92	4.03	6.34	1.2
ANNUAL AVERAGE	1.33	4.12	3.84	1.49

*solar load per unit floor area within the perimeter zone per facade (BTU/ft² hr)

Maximum solar radiation received annually by the west facade is 4.12 (BTU/ft² hr) and minimum solar radiation received by north façade is 1.33(BTU/ft² hr), as shown in Table 5.

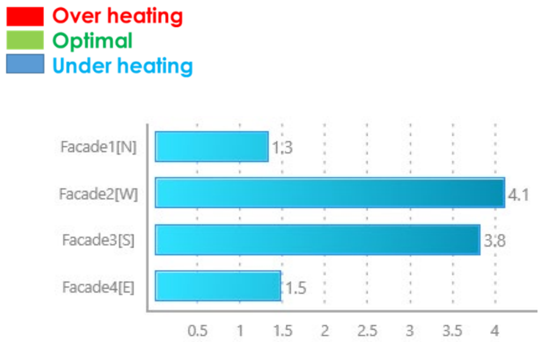


Figure 13. Annual average under heating solar radiation received by each facade in Module-4

Figure 13 shows that the building facades receive under heating solar radiation throughout the year on each facade. The façade material blocks the maximum solar radiation and optimal heating is received inside the building.

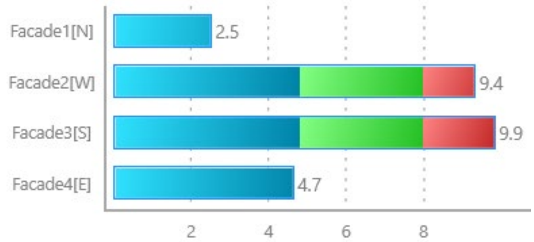


Figure 14. Peak solar heat in Module-4

Maximum solar heat is received by the south facade of the building, and minimum solar radiation received by the north facade of the building or optimal heating (Figure-14).

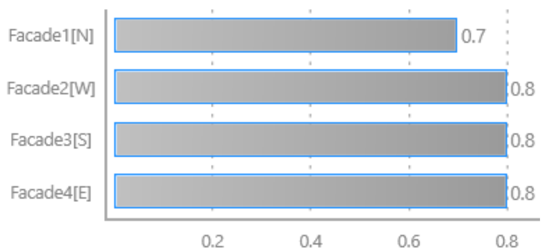


Figure 15. Module-4, daylighting chart

Very low daylight is received by each facade of the building as shown in Figure 15. Daylight received annually is 0.78%, which is very low. It will increase the load of artificial lighting and electricity bills but solar radiation is much lower.

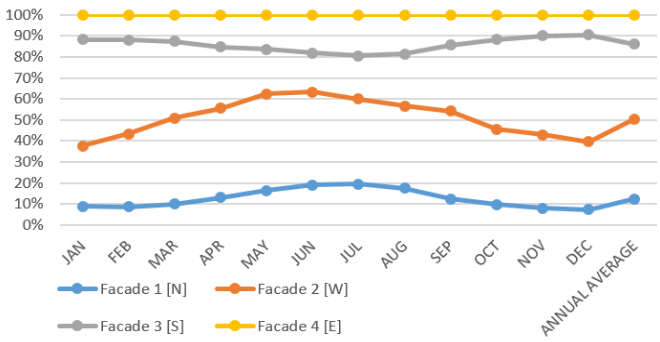


Figure 16. Monthly and annual solar load received by each facade of the building

Maximum solar radiation is received by the west facade in July (Figure 16).

6. Results of the simulation

After the simulation and analysis, the results are obtained from module-1, module-2, module-3, and module-4. The results show annual facade receiving maximum solar radiation (from 01 January 2021 to 31 December 2021) which covers all the working hours of office 7:30 am to 18:00 (6 pm) in May, June, and July and annually western facade receives maximum solar radiation throughout the year, whereas minimum solar radiation is received by northern facades. The main result is achieved by calculating three building factors; glazing, solar loads, and daylighting.

The analysis and the comparison between the four simulated modules highlight the importance of impact of materials. It also explores the daylighting received by the various facade materials and its impact on the results. Simulation is done on different facade materials and their properties, and the direct solar radiation entering inside the building through various facades. Simulation is done on various facade materials and their different U-values, Module-1: Double glazing domestic SC=0.4, its U value is 0.32 BTU/(sqft. F hr) and R-Value 1.9 sqft.hr/BTU, Module-2: 6mm Optiblue,1/2" Air, 6mm Solarbar 67(3), its U-value is 0.28 BTU/(sqft.F hr) and R-Value 3.59 sqft.hr/BTU, Module-3: SunGuard, DS Bronze 30/23 Double glaze, its U value is 0.28 BTU/(sqft. F hr) and R-Value 3.49 sqft.hr/BTU, Module-4: Double Low-E (argon) with ext. woven shade, its U value is 0.32 BTU/(sqft. F hr) and R-Value 5.62 sqft. hr/BTU. The lower U- value reflects better results as the facade reduces the transfer of heat and the higher the R-value means better is the insulation of the material.

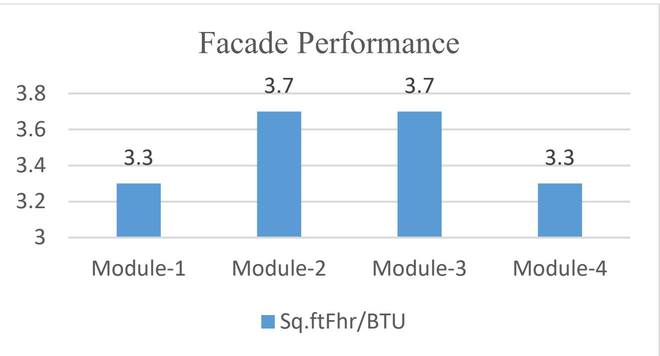


Figure 17: Building facade performance of different modules

Facade Performance: The different facade materials are used in modules with different properties and have an impact on facades performance. Performance of facade materials are, module-1 is 3.3 sq.ftFhr/BTU, module-2 is 3.7 sq.ftFhr/BTU,module-3 is 3.7 sq.ftFhr/BTU, module-4 3.3 sq.ftFhr/BTU (Figure 17).

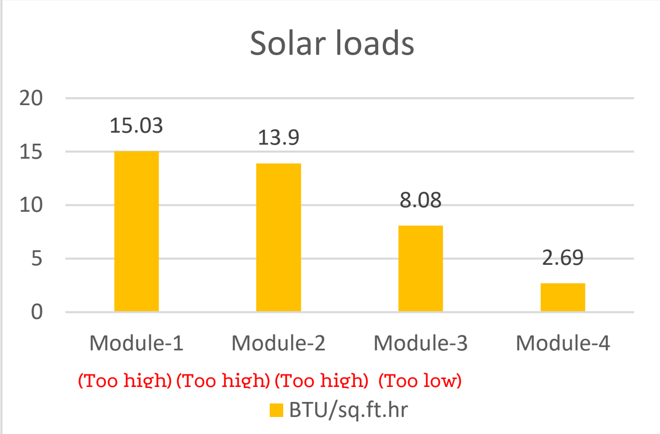


Figure 18: Solar loads received by building facades in different modules

Solar Loads: All the building facades are receiving solar heat gain throughout the year. Different modules received different solar loads due to different materials used. Module-1 received 15.03BTU/sq.ft.hr (too high), Module-2 received 13.9 BTU/sq.ft.hr (too high), Module-3 received 8.08 BTU/sq.ft.hr (too high), and Module-4 received 2.69 BTU/sq.ft.hr (too low) as shown in Figure 18.

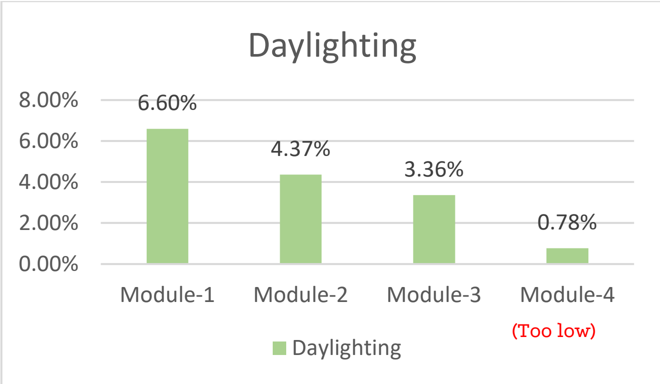
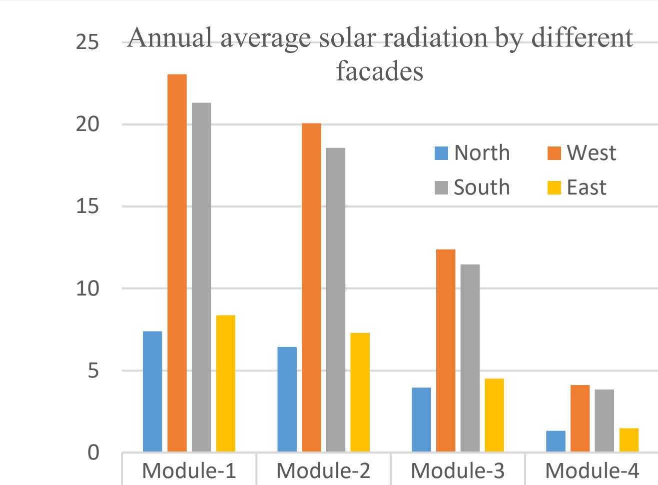


Figure 19. Daylighting received by building facades in different modules

Daylighting: Daylighting received by building interior spaces the amount of natural light entering inside the building. The maximum daylighting is received by module-1 6.60% and the minimum daylighting is received by module-4 is 0.78% (too low), shown in Figure 19.



	Module-1	Module-2	Module-3	Module-4
North	7.39	6.44	3.96	1.33
West	23.05	20.07	12.39	4.12
South	21.33	18.58	11.48	3.84
East	8.37	7.29	4.5	1.49

Figure 20. Annual average solar radiation received by different facades of different modules

Comparative analysis of different modules that received solar loads annually is presented in Figure 20. Maximum solar radiation is received by module-1 and the minimum by module-4.

7. Conclusion

The facade is one of the most significant contributors for the energy consumption, economical, and comfort parameters of any building. From the different simulation analyses, it has become clear that facade materials and different strategies help to reduce the power consumption of building from artificial cooling and provide thermal comfort inside the buildings. The primary purpose of climate responsive facades is to provide a barrier between the interior and exterior environment and consider the commonly considered facade materials of the building directly affected by the solar radiation and transfer heat from outside to inside areas.

From the simulation and analysis result, it is clear facade materials contribute in reducing the solar radiation with the help of facade materials. This research shows that the maximum solar heat gains and poor facade performance are achieved by module-1, as it receives maximum solar radiation transfer by material and facade performance is 3.3 sq.ftFhr/BTU. Module-4 received minimum solar load, daylighting too low and facade performance is minimum of 3.3 sq.ftFhr/BTU. In Module-2 and module-3, facade performance is similar i.e. 3.7 sq.ftFhr/BTU, but the solar load is quite high in module-2 and daylighting is better (4.37%). In module-3 solar load is less than module-2 but daylighting is also quite lower than module-2. If the office space requires good daylighting and better solar load, then module-2 is good for it. If the office space requires medium daylighting, then lower solar load and better thermal comfort are achieved by module-3, instead of module-2. Facade performace is found to be minimum in module-4.

The better results of module-2 and module-3 are based on facade performance, solar loads, and daylighting. If the office space requires maximum daylighting in the workplace, the solar load is higher in module-2. In module-3, if the office space receives better daylighting performance and solar load on facades are much lower than module-2.

Research aims to develop better understanding related to climate-responsive facade and facade materials and incorporate climate-based facades to reduce the penetration of heat inside the building. Such facades not only help in reducing the cooling load but also reduce the power consumption of building. The architects and designers need to incorporate different building facade, those will produce more climate-responsive building to make them sustainable and eco-friendly.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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PACE-2021
International Congress on the Phenomenological Aspects of Civil Engineering
Research Article 20-23 June 2021

Causes of Defects in Buildings and their Relationship with Life Cycle - Design, Construction and Post Occupancy Stage

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Keywords

Life cycle of building, maintenance cost, poor workmanship, faulty design, quality control.

Abstract

Defects have always been a matter of concern for stakeholders in construction industry, as they lead to additional running cost of project during the post occupancy stage. It is essential to identify the causes of these defects so that rectification measures can be expedited. For the purpose of research, the building life cycle is classified into three stages; design, construction and post occupancy. An investigation into the causes of defects is carried out through structured questionnaire survey based on Guttman's scale, from architects working in Indian construction industry. Twelve causes of defects related to different stages of building were examined. The descriptive data analysis and cross-tabulation of data resulted in some interesting facts. The research concluded that major causes of defects in buildings are associated with construction and post occupancy stage of building, and can be listed as; dampness/seepage in buildings, poor workmanship, lack of quality control, improper installation of services and lack of maintenance.

1.Introduction

Defects in building have an impact on the life cycle cost, as they are liable for huge investment, before the useful life of building is over. In context of a building contract, defect is defined as failure of the accomplished project to fulfil the quantity obligation and the implied quality (Cama, 2004). The life cycle of a building is comprised of four major stages; design, construction, post occupancy or maintenance, and demolition stage. The defects occurring in a building have direct relationship with the quality of work and it must be related to cost to achieve the total quality management system (Abdelsalam and Gad, 2009). Hasan et al. (2016) argued that improved workmanship, identified responsibility for all parties, frequent meetings for evaluating progress, selection of good quality building materials, usage of modern construction methods, readable drawings, compliance with specifications, regular and proper inspection on site, are most effective strategies for minimising defects in building construction projects. Incorrect methods of construction, selection of poor materials and bad labour practices lead to design and construction defects (Olanrewaju et al. 2010). Besides this, the maintenance management during post-occupancy stage also contributes towards the life cycle cost of building. It is presumed that the likely causes of these defects have their roots underlying in different stages of a building, i.e., design, construction and post occupancy stage. The endeavour of this research is to investigate these causes of defects and establish their relationship with the different stages of building. The opinion of architects in India, are collected for data analysis.

2. Literature Review

Defects can be divided into two categories; based on their occurrence time and nature of defect. The defects are sometimes referred as patent and latent defects, which are related to their time of occurrence. Latent defects are hidden defects caused by the designers that become apparent at some later date, whereas patent defects are caused by the constructer (Cama, 2004). Patent defects are can be discovered upon examination or in other words, these are shortcoming in a structure that are apparent to reasonable inspection (Chan, 2002). The nature of defects can be classified as structural and non-structural, depending upon the severity of damage caused or likely to occur in future. The defects have an impact on the life cycle cost, that is defined as, the current value of an asset over its operating life that includes; the initial investment cost, cost of occupation, operating costs, and also the profit earned after disposal of the asset when the useful life is over. Broadly speaking, the life cycle costs can be classified as; Capital costs, Costs-in-use, and finally the costs involved in disposal of the property. The capital cost includes cost of construction including all services. The maintenance costs are a component of cost-in-use, considering all recurring costs. The running, repairs and replacement required will cover costs-in-use, and it is accepted that all of these are subject to be considered well during the design process (Chanter, B. and Swallow, P., 2007). The activities performed during three stages; design, construction and post-occupancy, need to be examined in order to further investigate on their relationship with the defects and their causes.

Bakri and Mydin (2014) have summed up structural defects as: Cracks in walls caused by overload or because the structure has settled or heaved; Unstable Foundation because of movement of the soil, faulty design, overload (Dead and Living Load), material strength, or natural Disaster. Borku, W.T. (2020) state that structural defects in roof, stairs, cracking door and window are caused likely because of poor quality of construction materials, poor workmanship, lack of site supervision, poor construction practices or mix design problems. Bakri and Mydin (2014) have also identified non-structural cracks in buildings, such as: Peeling paints (interiors) due to poor surface preparation; Peeling paints (exteriors) surfaces due to exposure to the rain, sun, thermal variation, and new plastered or skimmed walls or ceiling are not given enough time to completely dry before painting; Dampness due to rain, condensation, flooding, service leaks, construction process, or improper usage of building; Non-biological deterioration in timber because timber in service being subjected to environmental exposure, living organisms such as insect infestation, fugal decay and marine borers, design alterations, poor maintenance, wood boring insects, fungal decay; Mold and fungi due to water damage, high humidity, or dampness; Cracks due penetration of rain to the external surface of structural; Manmade holes; Plaster falling off from ceiling because of vibration due to usage; Shrinkage Cracking due to usage of strong mixes of render on weak or bad prepared background; defects of Rendering (exterior plaster) due to loss of bond between coats, surface cracking, friable powdery surfaces, water damage from overflowing tub, leakage in the toilet or shower, seep out of plumbing or roof, storm damage, cracks around a chimney or movement of structure. Borku, W.T. (2020) also stated some non-structural defects such as: Honeycomb, Peeling of paint, Dampness penetration, Vegetable growth on buildings due to poor maintenance, poor project management, poor quality of construction materials, poor workmanship, lack of site supervision, and poor construction practices. Lack of coordination of design work, errors in production planning, erroneous craftsmanship, and late deliveries are common defects (Josephson and Hammarlund, 1999).

Natural hazards are unpredictable and so are the defects related to them. These hazards may cause damage ranging from minor cracks to collapse of the structure. The codes provide some provision to design buildings taking safety measures, so that collapse can be prevented. However, the probability of defects occurring due to natural hazards including movement of soil beneath the building due to earthquakes cannot be ignored. Gryna (1988) defines cause as a demonstrated basis for the occurrence of a defect. Hence, it is essential to focus on causes of defects during different stages of building project.

a. Defects and the Design stage

The design stage has the greatest scope for technical performance problems to originate. It is assumed that poor detailed design practices can contribute towards performance problems during the later life of a building. In other words, the real cause exists during an earlier stage. The defects occurring during the later life of a building may be easily associated with the detailed design stage. The introduction of high technology in building construction demands greater emphasis on the need to co-ordinate design from both perspectives, i.e.; technical and organisational. There is a need for better co-ordination i.e., design management practices, and checking systems (Chanter, B. and Swallow, P.,2007). Hasan et al. (2016) highlighted causes such as poor design, low-quality workmanship, construction not according to design, or exposure of the building to variables not accounted for in the design, as liable for defects in construction project. The study also considered the impact of the design's buildability on the quality of work and the long-term durability of building materials.

b. Defects and the Construction stage

Defects can occur in a building during construction stage, defects liability period, and post defects liability period also. It has been verified that most defects occurred during construction stage (Ede, 2010). A study was conducted by Chong and Low (2005) to investigate defects at construction stage of building, and it was observed that internal wall defects accounted for 89% of all defects, with workmanship problems as the cause of defect. As per the building feature and stage of occurrence, the following causes were investigated: the frequency of design, workmanship, material, lack of safety, and maintenance. Chanter, B. and Swallow, P. (2007) emphasized that execution on site is an important stage and site supervision, checking of materials on site, and workmanship must be focussed on. However, employing building materials of low quality is identified as main cause of building collapse (Oloyede et al., 2010) and high maintenance (Hashim et al, 2015). Isa et al. (2016) researched for the causes of architectural defects in Malaysian university house and identified most common causes as; work did not meet specifications, poor workmanship, lack of safety, vandalism, and water seepage. According to Kim et al. (2019) defects are mostly caused by human or process errors and there are a few causes of defects in residential buildings, such as; lack of control, accelerated schedules, construction by inexperienced staff, material defects, and insufficient inspection.

c. Defects and the Post occupancy stage

Chanter, B. and Swallow, P. (2007) emphasised that a considerable number of construction failures are contributed due to poor maintenance practices, like; inadequacy of routine maintenance, non-implementation of an ineffective replacement planning, lack of regular and proper inspections, non-availability of data to enable the maintenance so that it can be properly carried during the post occupancy period. The buildings may last for centuries, if they are properly maintained. It is also of crucial significance that the maintenance managers are involved at the design stage.

Chong and Low (2005) found that at the occupancy level, mechanical and electrical components accounted for 73 % of defects caused by design flaws. Incorrect installation affects construction project efficiency and workmanship, design, management, equipment, material, or lack of safety of already installed objects are the most common sources of defects traced in construction projects. These defects can be associated with adjustments, mistakes, omissions, or harm (Alencastro et al., 2018).

2.4 Cost of defects

According to Ali et al. (2010), the building maintenance efforts in the United Kingdom have surpassed 50% of all annual construction operations. According to studies, 70-85 percent of building maintenance and running costs can be controlled during the design stage. It accounts for a significant amount of total building life cycle costs, and there has been a recent rise in awareness of the need of budgeting for building maintenance and operations (Krstic and Marenjak,2012). Josephson and Hammarlund (1999) stated that the defect costs account for 4.4 percent of total manufacturing costs. The time it takes to correct them is about 7% of the overall time spent on the job. Rework of defective components discovered late during construction wastes 6-15 percent of construction costs, while rework of defective components detected during maintenance wastes 5% of construction costs (Akinci and Boukamp, 2004).

3. Research Methodology

The literature review highlighted issues related to likely causes of defects during life cycle of building. These causes can be summarised as; natural hazards, movement of soil beneath the building, dampness/seepage in building, inadequate drainage system, faulty design, poor workmanship, faulty plumbing, lack of quality control on building material, non-adaptability of building for future demands, improper installation of building services (during construction and post occupancy), alterations during post occupancy, lack of maintenance.

3.1 Research questions

The research aimed to investigate the causes of defects those are related to different stages of building life cycle i. e., Design, Construction and post occupancy. Further, it also aims to explore whether the professional experience, in terms of number of years and exposure of respondents changes their opinion towards the causes of defects. An attempt was made to enlist the possible causes of defects through literature survey and conduct a questionnaire survey to analyse the research questions.

3.2 Instrument design and data collection

In order to investigate the causes of defects in buildings during life cycle of buildings, an online structured close-ended questionnaire was designed and the survey was conducted through a non-probability sampling method. The questionnaire consisted of two parts. Part A comprised of questions related to the profile of respondents and included a set of closed-ended questions with a single choice. Part B comprised of twelve causes of defects. Attitude scaling was adopted based on Guttman's scale that helps to measure the composite scores (Dixit, 2011). The target group were 200 architects with variation of professional backgrounds, such as:

academicians, practitioners, and both. Akintoye (2000) have stated that receiving 20-30% response is acceptable in the construction industry and the response rate for the survey conducted as 62%, that can be assumed to be acceptable.

4. Data Analysis

The demographic profile concerned the profession category, experience, and budget of the projects handled by respondents. The highest response rate was from practicing architects (64.7%) and from architects having experience of 0-20 years (87.9%). Majority of architects (62.9%) had an experience of handling projects of budget above 5 Crores. The descriptive analysis conducted for 'Part A' was based on three indicators of architect's profile as illustrated in Table 1.

Table 1. Demographic profile of respondents

Profile	Category	Frequency (n)	%
Professional Experience/ Job position	Academicians	11	9.5
	Practicing architects	75	64.7
	Both	30	25.9
Working experience	0-10	66	56.9
	11-20	36	31.0
	21-30	8	6.9
	31-40	3	2.6
	Above 40	3	2.6
Budget of projects	30-50L	10	8.6
	51L-1.5Cr	7	6.0
	1.6-2.5Cr	9	7.8
	2.6-5.0Cr	10	8.6
	Above 5.0Cr	73	62.9
	Not applicable (for academicians)	7	6.0

% - percentage, n- sample response, L-Lakh, Cr-Crores

The general perception of respondents regarding the causes of defects is demonstrated in Figure 1.

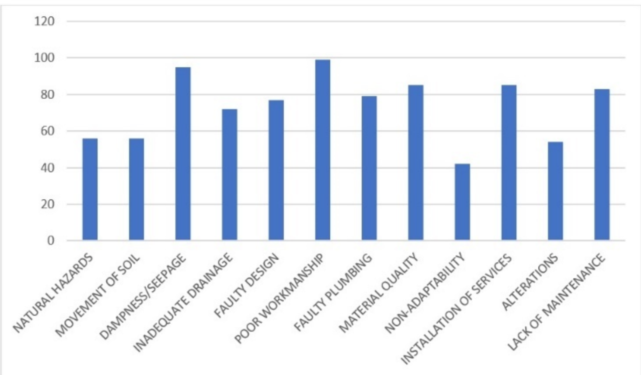

Figure 1. General perception for causes of defects

It is observed that highest response is received for poor workmanship (86.1%), dampness and seepage in buildings (82.6), lack of quality control and improper installation of building services (both at 73.9%), and lack of maintenance (72.2%). Lowest response is in favor of non-adaptability of buildings for future demands (36.5%).

A descriptive analysis of the data was also performed to obtain frequencies and cross-tabulation of data was conducted on the basis of their experience, profession and budget of projects handled, as presented in Figure 2, 3, and 4 respectively.

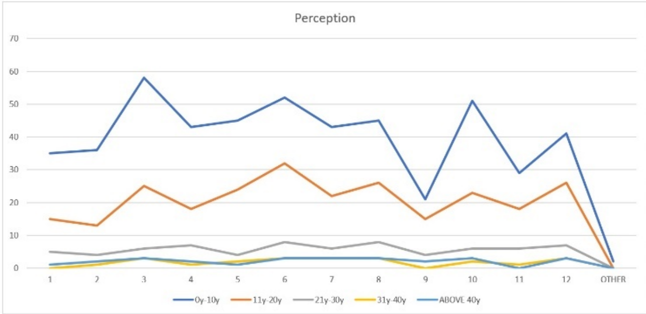

Figure 2. Cross tabulation of experience of respondents with causes of defects

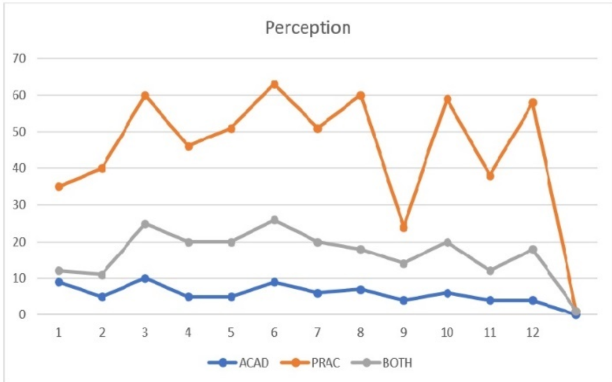

Figure 3. Cross tabulation of type of profession with causes of defects

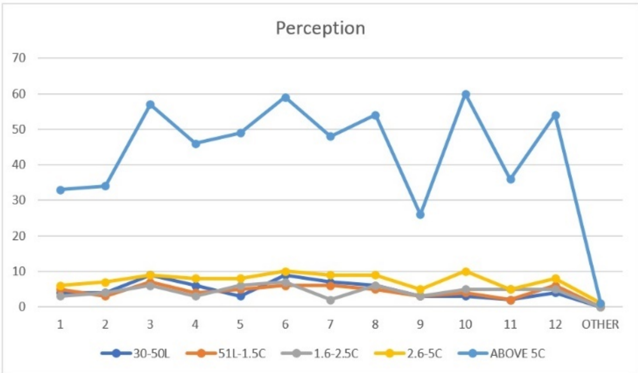

Figure 4. Cross tabulation of budget of building with causes of defects

On close examination, it is observed that the profile of responses for various causes of defects is similar when cross-tabulated with years of experience and profession. On the contrary, the response received from projects above 5 crores of budget are distinguishably different from all other projects of lower budget. A comparative description of frequencies for responses obtained after cross-tabulation is presented in Table 2, that includes data that is related to distinguishable frequencies only.

Table 2. Comparable frequencies for causes of defects

CAUSES	BUDGET (Above 5 Cr) n	Exp 0-10y n	Exp 11-20y n	Profession Practicing n
Natural hazards	33	35	15	35
Movement of soil	34	36	13	40
Dampness/seepage	57	58	25	60
Inadequate drainage	46	43	18	46
Faulty design	49	45	24	51
Poor workmanship	59	52	32	63
Faulty plumbing	48	43	22	51

Lack of quality control	54	45	26	60
Non adaptability	26	21	15	24
Improper services installation	60	51	23	59
alterations	36	29	18	38
Lack of maintenance	54	41	26	58
Other	1	2	0	1

n – frequency, Cr-Crores, y-years

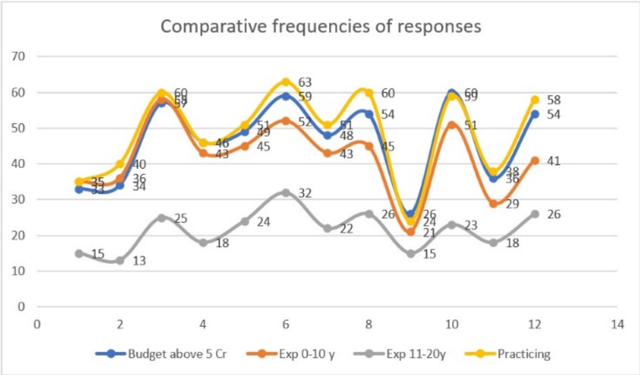

Figure 5. Comparative frequencies for causes of defects

It can be verified from Figure 5, that the most commonly recognised causes of defects in buildings identified by three categories of respondents; practicing, having 11-20 years of experience, and those who have handled projects above 5.0 Cr, are dampness/seepage in buildings, poor workmanship, lack of quality control, improper installation of services and lack of maintenance.

Further, an investigation was carried out to examine the significance of the relationship between the opinion of architect's having different professional background. A scatter diagram was plotted between the academician's response and practising architects' responses as shown in Figure 6. Scatter plot is a method of regression analysis or line of best fit (Oberoi, 2012). The scatter plot confirms the positive association between two categorical variables (Figure 6) i.e., similarity in responses towards the causes of defects in this case.

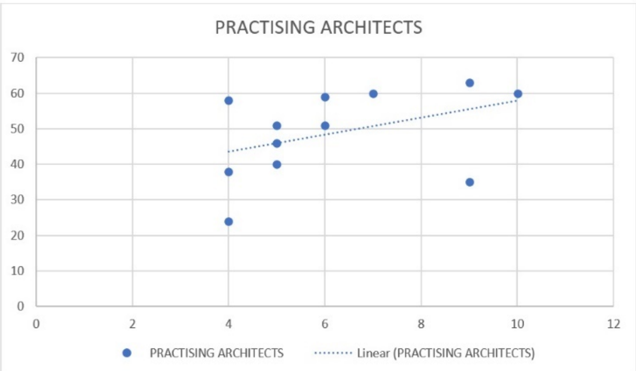

Figure 6. Scatter plot showing positive association between opinion of academicians and practicing architects

5. Conclusion

Exhaustive literature review was done to identify the causes of defects and they were further investigated through questionnaire survey to identify the most common causes. The three stages during life cycle of building were identified as; Design, construction and post occupancy. Further discussion is mandatory to classify these causes of defects in different stages of building life cycle. The causes of defects associated with the Design stage are; Inadequate design of drainage system (62.6%), faulty design (67%), non-adaptability of building for future demands (36.5%), and movement of soil beneath the building (48.7%). Movement of soil can be due to non-consideration of soil type during structural design exercise. The causes of defects related to construction stage are; poor workmanship (86.1%), faulty plumbing (68.7%), lack of quality control on building material (73.9), and improper installation of building services (73.9%). The causes of defects associated with post-occupancy stage are; dampness/seepage in building (82.6%), alterations (47%), and lack of maintenance (72.2%). Some causes such as natural hazards (48.7%) are unpredictable.

The opinion of respondents having professional experience in architecture of upto 20 years illustrates that the issues related to construction and post occupancy stage such as; dampness/seepage in buildings, poor workmanship, lack of quality control, improper installation of services and lack of maintenance, are critically responsible for defects in buildings. These responses are in coordination with the academician's opinion also (reference to Figure 6). It is also observed that non-adaptability of building for future demands, movement of soil beneath the building, alterations during post occupancy are not majorly responsible for defects in buildings.

6. Limitations of study and future scope

The research is conducted in Indian construction industry and is limited to the opinion of architects only. The opinion of other stakeholders from construction industry may vary from these results and prove some contradiction. Further analytical studies can be conducted to examine the understanding of different stakeholders and in different context of places.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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