Designing prosthetic architecture

Anosh Nadeem Butt*
Department of Architecture, Faculty of Engineering, University of Strathclyde, Glasgow G1 1XQ, UK

Abstract— The paper aims to explore and understand the ideas that contribute to the design of prosthetic architecture. The objectives to achieve the aim were: (1) to investigate "prosthetic building design" through previously published research, and (2) to design prosthetic architecture in an academic environment. The research opted for a systematic literature review assessing all accessible research related to prosthetic building design. It was complemented by the conceptualization and prosthetic architectural design of a Graduate design studio presented through various drawing techniques. The paper provides empirical insights such as achieving the design of prosthetic architecture by using representative qualities that are objectively proportionate to existing building elements but simultaneously reinforce their novel character. Due to the chosen research method, the research results may lack generalizability to other types of buildings requiring a prosthetic hence researchers are encouraged to test the proposed outcomes further. The research fulfils an identified need to study how prosthetic architecture can be designed.

Index Terms— Architectural Design, Building Extension, Design Evolution, Evolutionary Architecture, Extension Design, Prosthetic Architecture, Space Evolution.

1 Introduction

THE word 'prosthesis' is a Greek word that is defined as an addition, application, or attachment that replaces or adds to a body part to restore the normal functionality of the human body [1]. A prosthesis creates a relation between two distinct orders: flesh/steel, theory/fiction, translation/quotation, public/private, built/unbuilt, and so on [2].

Modern architecture is an interface that is a technological extension of the body neither natural nor cultural [3]. In the discipline of architecture, a prosthesis is considered as an evolution of space. Like humans, buildings and cities grow, develop, and evolve [4], hence prosthetic architecture is needed. An immediate and practical consequence would be that architectural designs should be instilled with characteristics for future extensions of buildings to be healthy rather than cancerous [4]. Several participants are needed to design a building that consists of architects, engineers, designers, planning authorities, and building clients.

It is predicted that by 2025 about 60% of the global population would be living in cities [5]. Currently, people living in cities contribute to 80% of greenhouse gas emissions worldwide [5]. The building industry is responsible for 40% of all carbon emissions, 72% of all electricity consumption, and 30% of all waste output [6].

Due to human migration patterns and negative environmental impacts of the construction, it is necessary to consider prosthetic architecture for the future of a sustainable built environment. The paper aims to explore and understand the ideas that contribute to the design of prosthetic architecture. The need for exploring these ideas is due to human migration patterns and negative environmental impacts on the natural environment.

Section II describes the research methodology used for this research. In Section III a systematic literature review with all the included studies is presented. It is followed by a case study of prosthetic architecture supporting and enhancing an academic environment. Section V highlights conclusions and topics of potential further research.

* *Anosh Nadeem Butt is currently pursuing PhD in Architecture from the University of Strathclyde, Glasgow G1 1XQ, United Kingdom, PH:+447404720816. E-mail: anosh.butt.2018@uni.strath.ac.uk*

2 Research methodology

To understand the ideas contributing to the design of prosthetic architecture, a systematic literature review (SLR) was conducted to identify research particular to the research topic [7]. The search string ''prosthetic building design'' was used for gathering studies available on ScienceDirect, Compendex, and Cambridge University Press, leading to the identification of 12,482 studies. The next step was to delete duplicates (9,560 studies), followed by screening by keywords from other fields (e.g., medicine, cancer, disease, drug, tissue). The remaining 3,740 studies were scanned by title and abstract, leaving 2,579 studies for which inclusion and exclusion criteria were established. Inclusion criteria entailed online accessibility of research papers published in English and related to prosthetic architecture. Exclusion criteria encompassed research papers from other fields such as electrical engineering, computer science, and manufacturing. Finally, a total of 10 studies were included in the systematic literature review. Table 1 shows the described SLR steps.

Table 1. Systematic literature review

	Repositories		
Steps	ScienceDirect	Compendex	Cambridge University Press
Identification	12482		
Screening	3740		
Eligibility	14		
Inclusion	10		

3 Systematic literature review

Nature has been a thematic connection within interdisciplinary debates to form potential bridges between natural sciences,

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social sciences, and humanities [8]. The first study shows that in the fields of architecture, planning, and urban studies; nature has mutated to 'neo-organicism' obscuring the ideological and historical perspectives [8]. Gandy [8] historicized the role of nature as a focal point for future research directions. The author mentioned nature's influence in the public arena across several research themes, such as stem cell research to nanotechnology, which presents a worrying contrast with the diminishing role for humanities and social sciences [8]. The research results reveal that the growing strength of natural sciences contributes to bringing arts and sciences under a common analytical framework and radically attempts to rework the idea of nature [8]. To support a common analytical framework emerging fields have been developed such as cybernetics, advanced prosthetic architecture, and the latest forms of artificial intelligence to underpin the well-established distinction between nature and culture to reevaluate the contrast between human nature and bio-physical systems [8].

There is a consensus among several researchers that prosthetic design is an emerging research field and needs theoretical and practical investigation [9]. For theoretical explorations, an interdisciplinary approach is required comprising of prosthetic design, product design, psychology, and fashion trends [9]. The authors reviewed literature and deduced that a successful prosthetic design needs the right balance between elements (parts of the design) and principles (rules guiding the structure). However, it is speculated that principles are self-sustaining and allow a designer to create the right design perception subject to variation from person to person, ensuring essential representation of 'innovation' in prosthetic design [9]. From this study, it is deduced that prosthetic design concepts need representative characteristics to make them feel objectively proportionate to existing elements while substantiating their novelty and personality [9].

Prosthetics may be used as tools in architecture to guide building users to operate in emergency cases where there is minimal chance of survival for people in an impact zone [10]. The study shows the critical assessment of environmental management as a co-habitation method with natural disasters such as Tsunamis and presents the post-disaster reconstruction of Constitución, a Chilean coastal city. The research results highlight that a geo-meteorological event that defies scientific calculability and social imagination causes absolute vulnerability and uncertainty but should not be used to express the need for fast or bold actions to 'save the planet' [10]. The authors argue that exceptional events need to humbly recognize the presence of excessive forces that cannot be managed diplomatically. It is advocated that easily identifiable luminescent prosthetic tools allow the planning and design of evacuation routes for predicted natural disasters.

For contributing to the right balance between elements and principles to achieve a successful prosthetic design [9], technological advances in fabrication methods are required to use metamaterials in design with hierarchy and length scales similar to those found in nature [11]. In the study, the authors confirmed that structural metamaterials and nanolattices can be created with enhanced mechanical properties at various scales ranging from angstroms and nanometers [11]. The authors deduced that the development of a material catalogue for prosthetic architecture needs a high surface-area-to-volume ratio of nanolattices that are useful due to their diverse applicability to building systems such as photovoltaic systems. The most significant finding of this particular study includes the overview of recent structural multidimensional metamaterials contributing to defining a multidimensional material design space to enable the manipulation of materials with unprecedented capabilities for prosthetic architecture [11].

Kurtis [12] goes into more detail in relation to novel material development and prosthetic architecture. The author identifies concrete as the most used construction material due to high societal demands. The study reviews recent advancements in three key areas having the potential to transform infrastructure design and construction: (1) supplementary cementitious material usage expansion and alternative supplementary cementitious materials, (2) increased use of alternative types of cement and binder technologies, and (3) evolving alternative reinforcement options. The results of this investigation include three strategies to facilitate and accelerate the practical acceptance of emerging next-generation materials and technologies from research and academia to industry that include: (1) standardized material evaluation, (2) site-production studies, and (3) modernization of industry-accepted design guidelines, building standards, regulations, and codes [12].

To facilitate technological advancement in fabrication methods and novel material development for prosthetic architecture, it is necessary to investigate startups and businesses that create new products and market opportunities [13]. Galvin et al. [13] present the dynamic interplay between materials and engineering for successful new products and industries. The research examines four technological companies in diverse industries that develop different material systems [13]. These companies consist of Rheonix, Kionix, Mezmeriz, and Incodema3D, and their products are based on novel polymer adhesion process, silicon microelectrochemical inertial sensors for thin films used in construction, integration of different classes of materials to optimize speed and displacement, and new fabrication processes of additive manufacturing of metals respectively. The research results deduced that for developing new products and creating new markets, tradeoffs in material selection, manufacturing processes, engineering design, and product performance are crucial [13].

Prosthetic architecture is associated with biomimetic systems that are defined as engineered parts embedded coherently to achieve increased functionality and superior resilience aided by robotics [14]. Campesato [14] compared the marketplace of robotics and prosthetics and concluded that the former is open to professionals and small businesses and diversifies offers to large competitors, whereas the latter deals with products and components likely to have emerged from 3D printing technologies [14]. The author correlated both marketplaces due to the common trend towards lightweight solutions and suggested the partnership between robotics and prosthetics to form the industrial robotics and prosthetic automation market. The envisioned combined marketplace would contribute to the design of prosthetic architecture.

The University of Florida formulated a multidisciplinary

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engineering design course for first-year undergraduate students to introduce concepts such as sustainable prosthetic prototypes [15]. The authors highlighted that the most significant objective was to help students develop early connections to instill a sense of care in students to design prototypes based on societal needs [15]. A few examples from the human-centered topics considered for first-year design prototypes included food stability (self-watering planters), sustainable energy (non-traditional power generation), and tools for disabilities (toys for children with prosthetics), etc [15]. The research results deduced that multidisciplinary engineering design courses based on a human-centered design enable students to acquire prototype design skills (solid modelling, 3D printing, sensors/actuators, microcontrollers, programming) and professional skills (teamwork, communication, critical thinking, and self-directed learning) [15].

Investigating the relationship between systemic thinking and design is fundamental to understand its correlation with design theory and practice [16] for possible application to prosthetic architecture. The research reveals four distinctly different interpretations of concepts of systems that include whether the system exists, what is systematized, how the system operates, and why the system exists. The study explained Richard McKeon's [17] definition of systems clustered into four broad groups representing modes of thought such as construction (a process by which parts are put together), discrimination (a process by which arbitrary formulations are interpreted), resolution (a process by which problems are resolved), and assimilation (a process by which surrounding truths are approximated) [16]. Buchanan [16] points out that McKeon [18] laid the foundation of the humanistic approach to communications and construction influential in the theory and practice development of design. The research findings include the identification of the underrated yet highly significant time period between 1968-1972 that extends the difference between artificial intelligence (AI) and the human control of AI through concepts of intelligence amplification (IA) [16]. These findings have a significant impact in relation to cybernetic organisms, the design of prosthetic architecture, and the future of the sustainable built environment as IA involves the effective use of information technology to augment, extend and enhance human intelligence through discoveries of various forms of bio-prosthetics.

The next section presents a case study of prosthetic architecture in an academic environment highlighting its conceptual framework, design process, and developed design proposal to support and strengthen ideas found in the systematic literature review.

4 Case study

Beaconhouse National University (BNU) was designed by one of Pakistan's most successful and celebrated architectural firms, Nayyar Ali Dada Associates (NADA). In 2017, for my B.Arch. thesis, I conceptualized and designed the Graduate design studio for the postgraduate program of architecture (M.Arch.) at Razia Hasan School of Architecture (RHSA) using prosthetic architecture at BNU. The existing structure entails a creative usage of the brick-clad reinforced concrete column grid (16′ x 16′) creating various volumetric spaces in the Department of Architecture. Among numerous challenges in relation to designing prosthetic architecture and the context was the strong existing character of the existing buildings due to reinforced concrete cladded with load-bearing brick. To address the challenge, representative characteristics were explored (Fig. 1) which are objectively proportionate to existing building elements [9]. The design research commenced by extensive documentation (Fig. 2) of existing buildings used by RHSA, which included plans, sections, digital modeling, and physical modeling. The research included various volumetric experiments to explore the most successful prosthetic for RHSA (Fig. 3, Fig. 4).

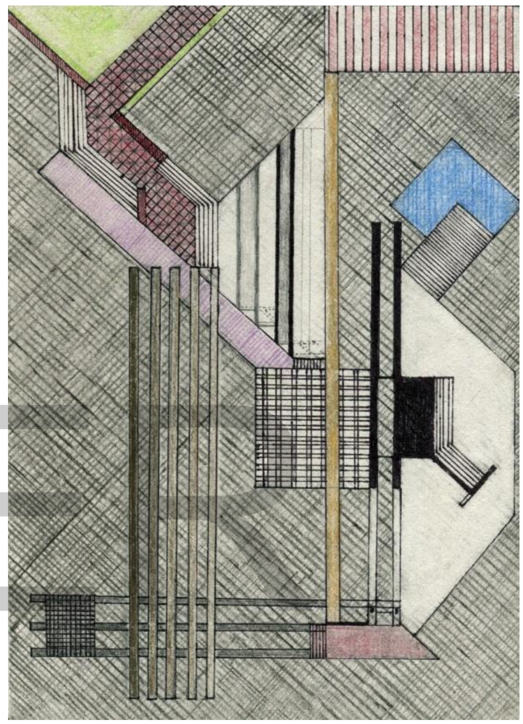

Fig. 1. Agglomeration of space at Beaconhouse National University.

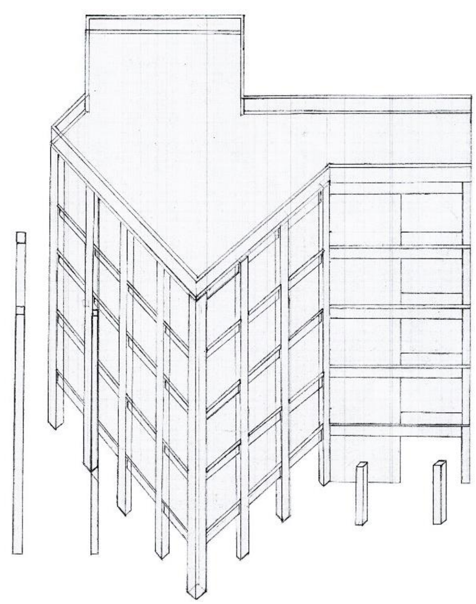

Fig. 2. Vertical Axonometric of existing building.

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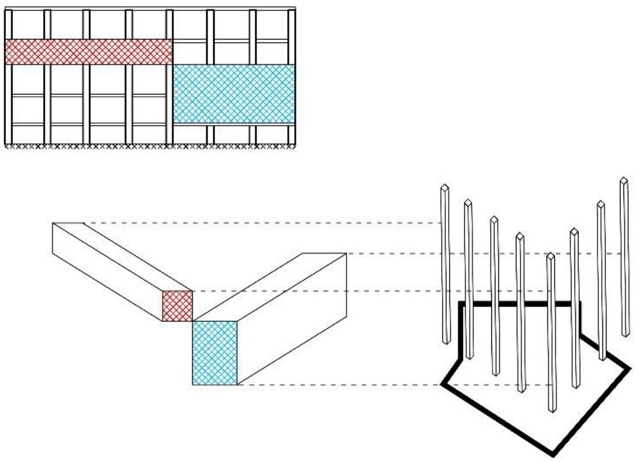

Fig. 3. Volumetric experiment to discover a prosthetic for RHSA.

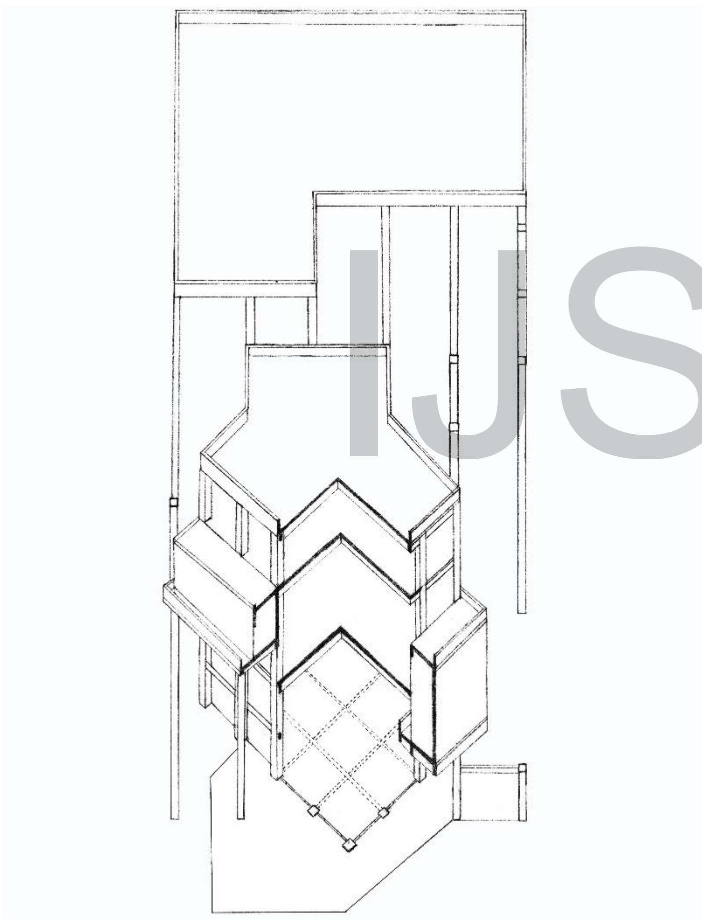

Fig. 4. Corner cut vertical axonometric of one of the volumetric experiments.

These experiments were followed by considering the tectonic expressiveness as a cornerstone when translating a prosthetic to a site. Steel was investigated as a material for the prosthetic architectural design of the Graduate studio as it allows the expressive characteristics offered by the site. The interplay between steel and brick-clad reinforced concrete columns required exploring construction details to understand existing façade conditions and current geometrical details (Fig. 5).

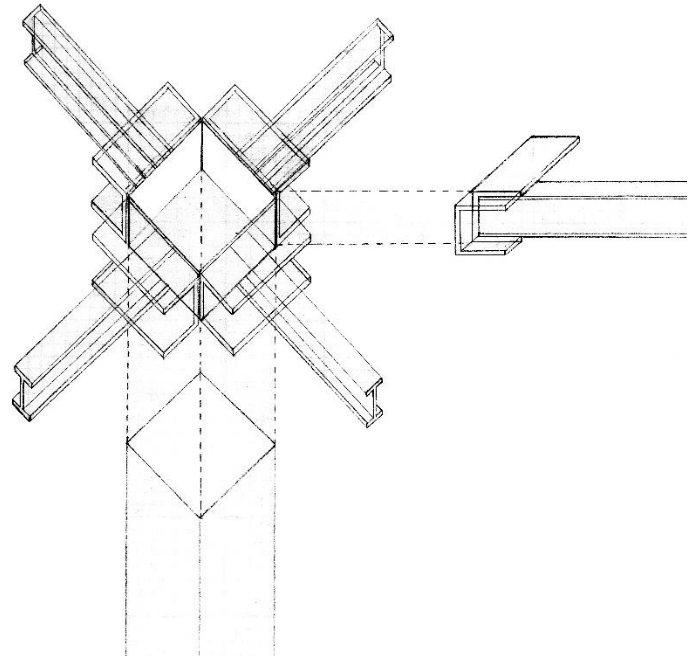

Fig. 5. Steel channel section forming a collar around the reinforced concrete column and allowing I-beams to support the new prosthetic construction.

The study of construction details revealed their importance, regarding them being an inspiration for future postgraduate students at the Graduate studio at the Department of Architecture. Another predominant idea involved designing the horizontal circulation like in a panopticon (Fig. 6). It shows three explorative possibilities for integrating a panopticon-like circulation into the prosthetic design of the Graduate studio. Spaces marked in red show spatial volumes proposed as design studio spaces, yellow showed the horizontal circulation of the design, and blue marked voids. Fig. 6a shows peripheral movement from the undergraduate studio spaces allowing postgraduates to glimpse design processes from junior years. Fig. 6b shows movement into the junior undergraduate design studios forming a direct visual connection, and exhibiting the creative potential of junior undergraduate students. The design approach shown in Fig. 6c presents a mixed strategy as the pathway moves externally in the junior studios and moves internally through the studio of final year undergraduate students. Generally, a panoptical circulation in design creates vantage points and visual connections for postgraduate students to look towards undergraduate students (Fig. 7, Fig. 8).

Fig. 6. Exploring the possibilities of panoptical circulation.

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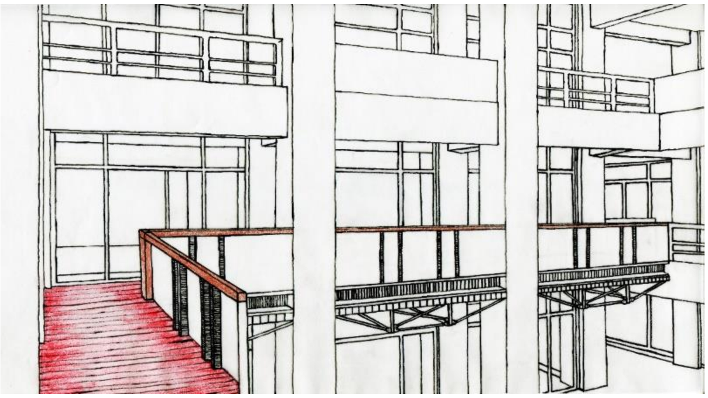

Fig. 7. Panoptical pathways outside undergraduate studios.

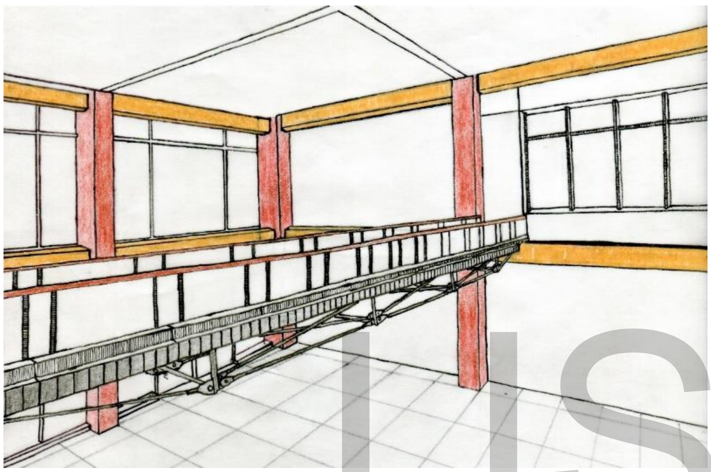

Fig. 8. Panoptical pathway inside undergraduate studios.

Other ideas pointed out during the design process included inversion as a concept due to the existing structural system. All the existing buildings at the university have a reinforced concrete frame that allows a prosthetic to be structurally resolved using a suspension system (Fig. 9). The envisaged suspended system would create distinct spaces similar to its context, such as social interactive spaces, communal spaces, and confined reading spaces (Fig. 10).

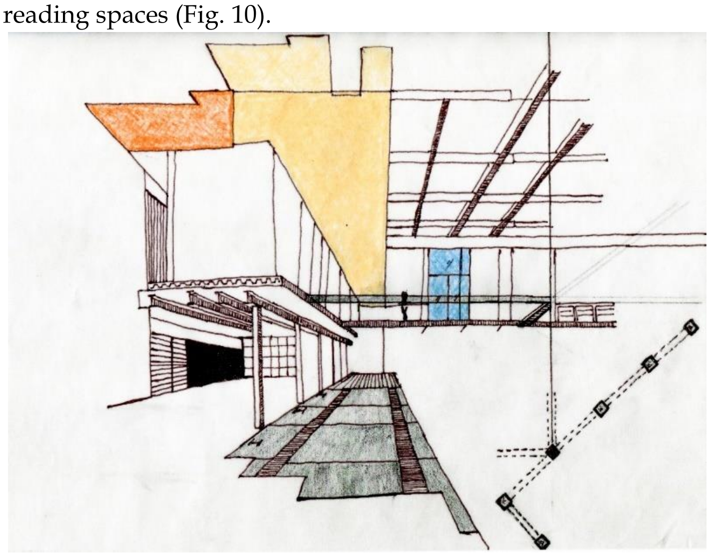

Fig. 9. Conceptual drawing of suspended structural system.

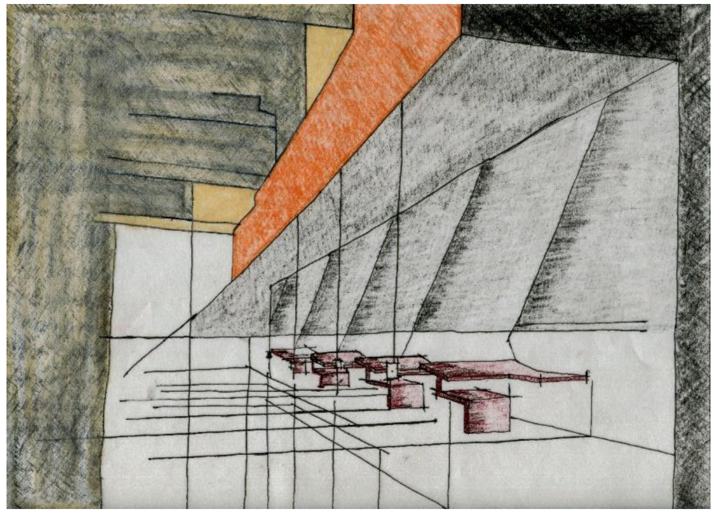

Fig. 10. Conceptual drawing of communal reading space.

After detailed volumetric experimentation, extensive construction detail exploration, and diverse spatial and structural conceptualization, a site (Fig. 11) was identified that would connect existing horizontal circulation, connect passageways with faculty offices, and develop a floor plan on the mezzanine levels of the architecture design studios as an outcome of pure axial arrangement. The chosen site also resolves the current imperfect dimension of the Architecture Courtyard (40′ x 48′) and spatially corresponds to the quality of the void-like space to create a 40′ x 40′ space due to the additional light shelves present next to the courtyard.

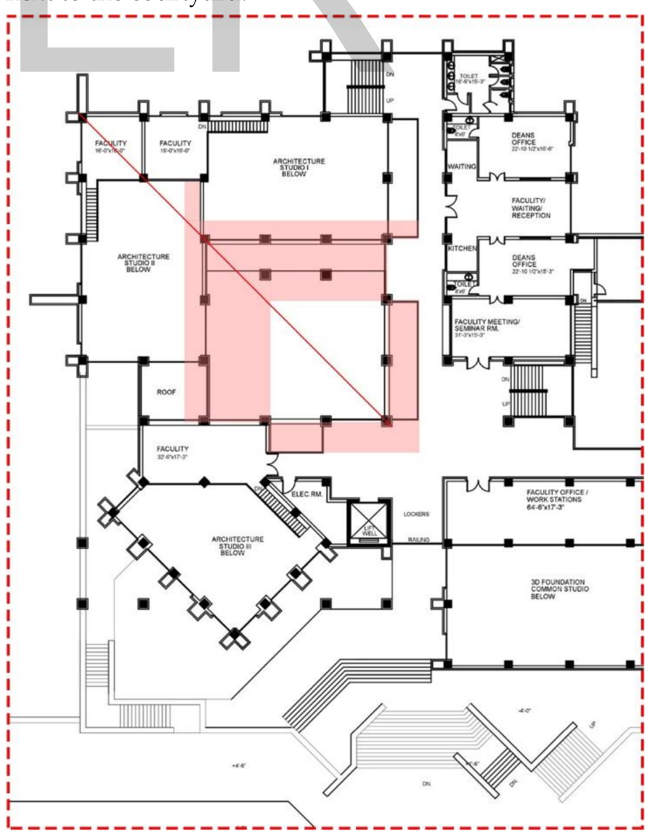

Fig. 11. Chosen site for Graduate design studio.

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4.1 Plans

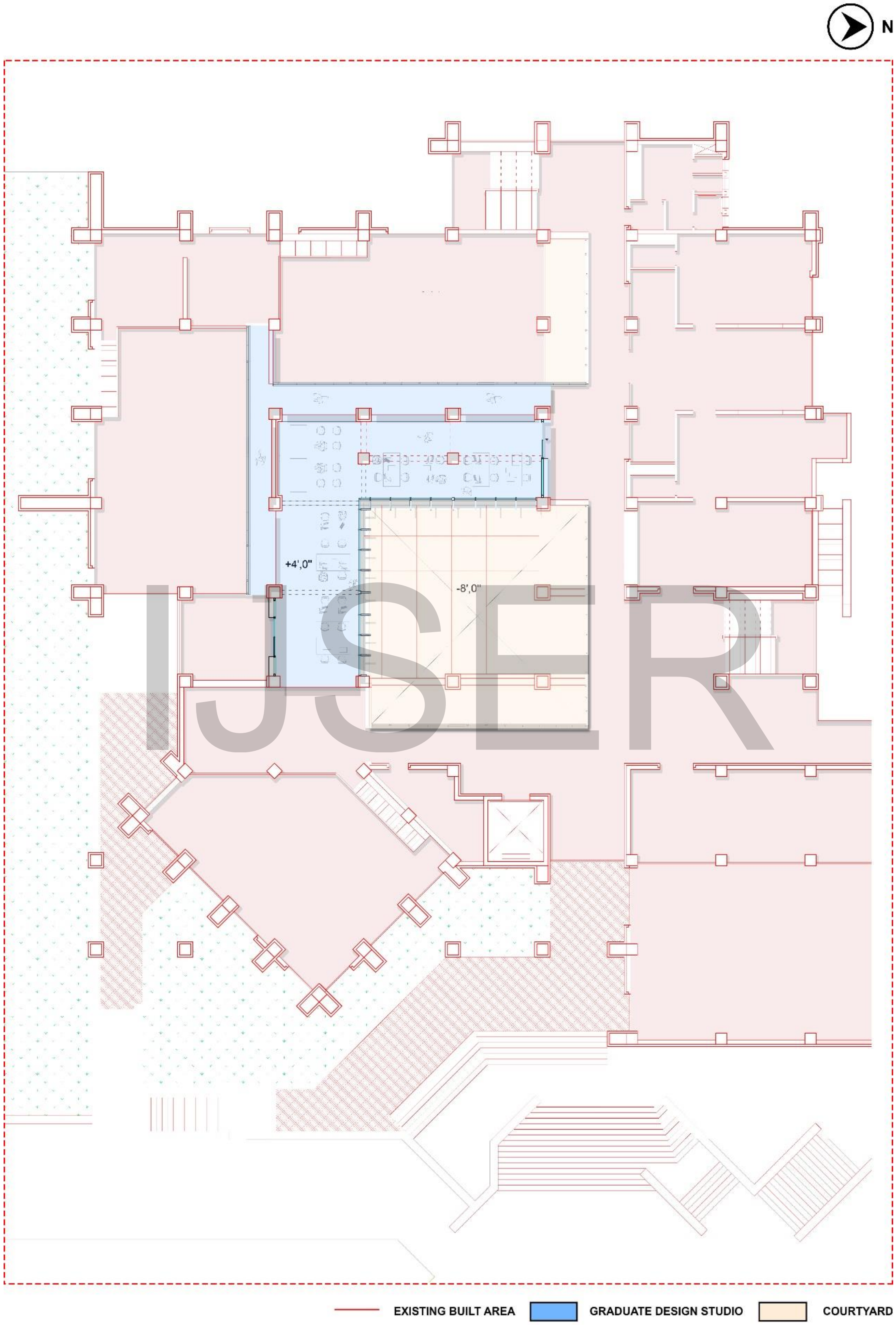

Fig. 12. Plan at 8',0''

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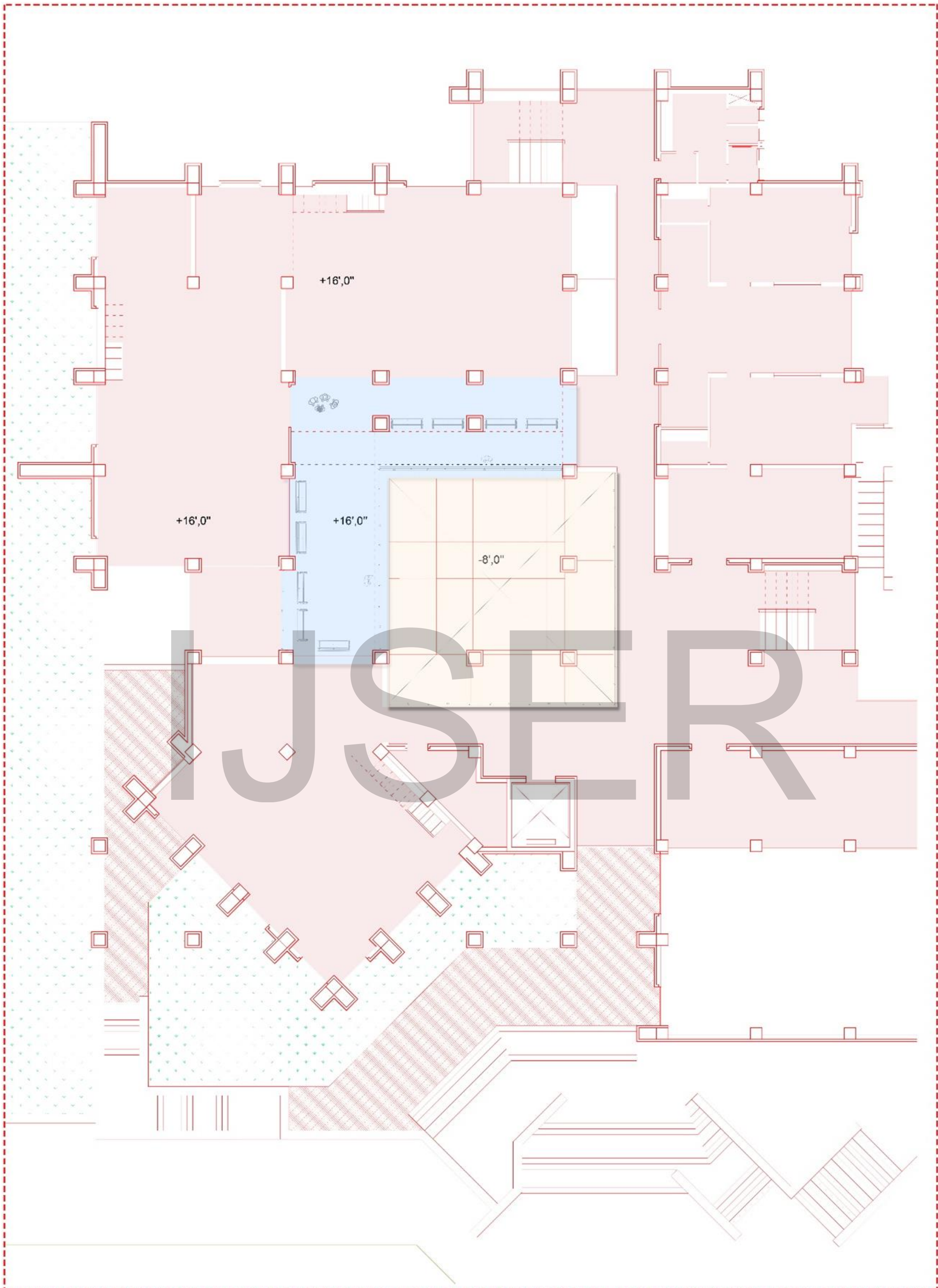

Fig. 13. Plan at 20',0''

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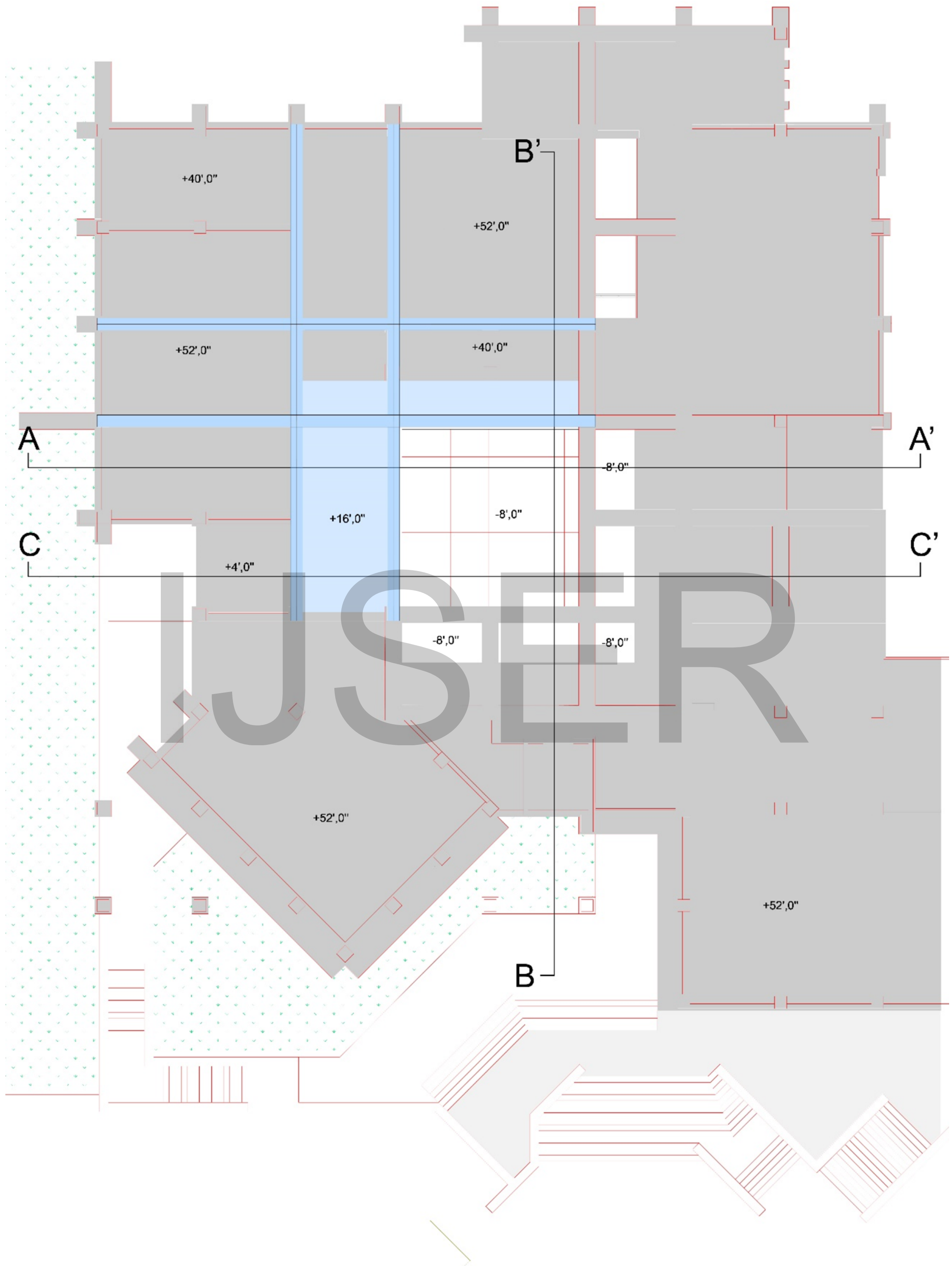

Fig. 14. Roof plan

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4.2 Sections and details

Fig. 15. Section AA'

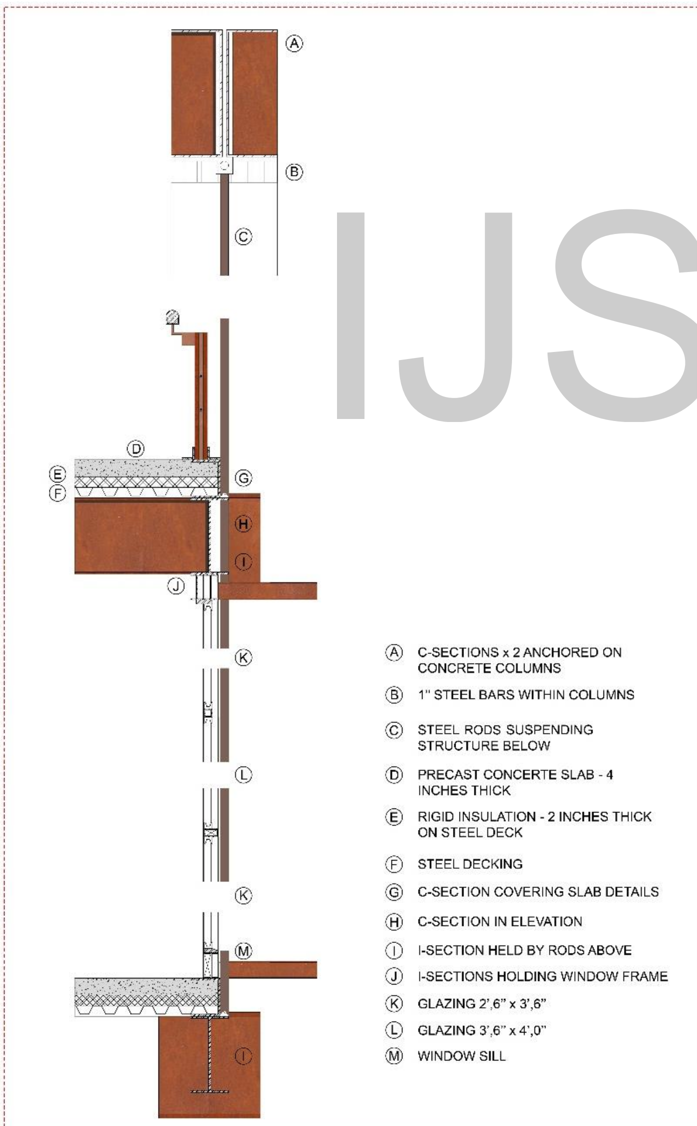

Fig. 16. Detail A.

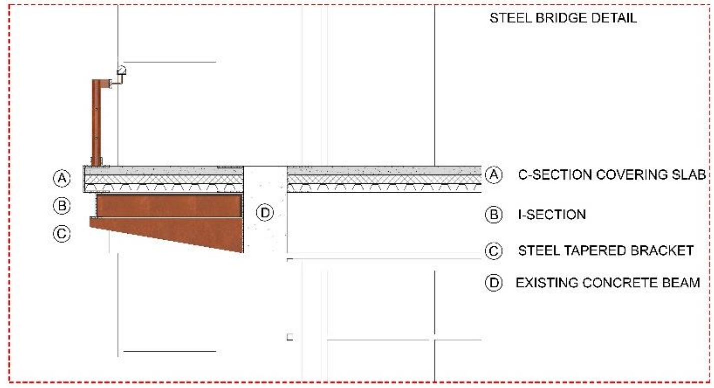

Fig. 17. Detail B.

4.3 Renders

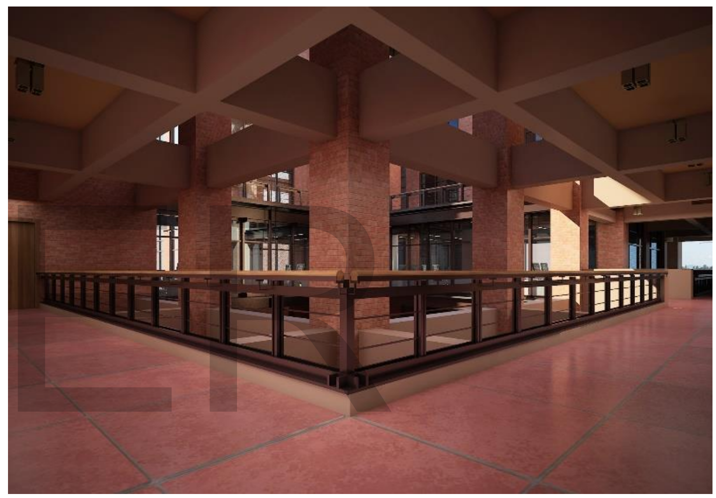

Fig. 18. View showing design intervention and new void spaces.

Fig. 19. Elevational view towards the Graduate design studio.

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Fig. 20. Viewing the courtyard from the Graduate design studio.

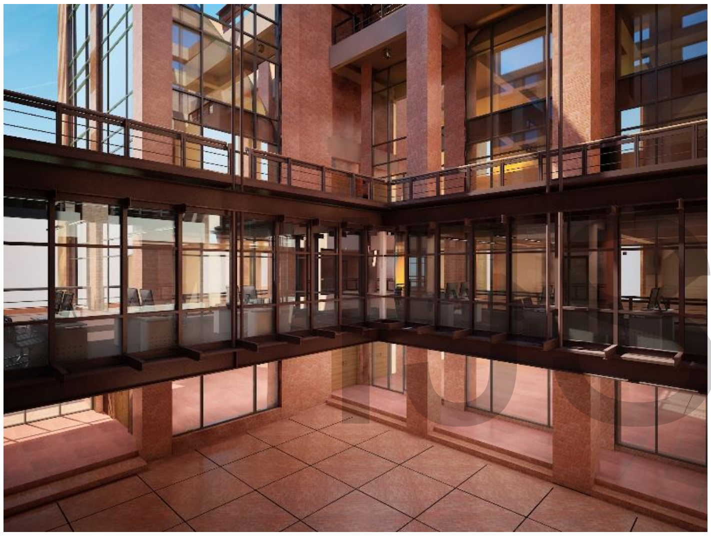

Fig. 21. Perspective of the intervention and the Architecture Courtyard.

4.4 Summary

The innovative concept and prosthetic architectural design of the proposed Graduate design studio represent existing building qualities and simultaneously substantiates its characteristics by introducing steel as a novel material to the context of Beaconhouse National University.

The design of the created space fundamentally combines several building materials, which would cause students to be fascinated by Miesian construction details. The Graduate design studio provides visual corridors due to existing double-height spaces and creates vantage points that allow the ecosystem of multiple architectural educational levels to thrive.

The insular planning of the Graduate design studio provides advantages such as natural ventilation, visual connectivity, and assists in reforming the Architecture Courtyard into a perfect square. The prosthetic architectural design of the Graduate design studio contributes to connections to the faculty offices from the Dean's offices. Intrinsically the prosthetic assists the hypothesis and objective of educational empowerment within the Department of Architecture.

5 Conclusion

The paper aimed to explore and understand the ideas that contribute to the design of prosthetic architecture. The objectives to achieve the aim were: (1) to explore ''prosthetic building design'', and (2) to conceptualize and design prosthetic architecture in an academic environment. A systematic literature review (SLR) and a case study was conducted to achieve the aim and objectives. The SLR highlighted ideas related to prosthetic architectural design by researchers from around the world since 2008. The review identified how nature forms thematic connections between disciplines from natural sciences, social sciences, and humanities. The investigation presented the need for developing a common analytical framework that culminates to the growing strength of natural sciences contributing to arts and sciences supported by emerging fields such as cybernetics, advanced prosthetic architecture, and the latest forms of artificial intelligence. The findings also showed that a successful prosthetic design needs the right balance between elements (parts of a design) and principles (rules guiding the structure). This balance is necessary for instilling proportionate representative qualities of existing building elements while substantiating novel characteristics through distinct materials. The right balance between elements and principles for a successful architectural prosthetic needs technological advances in fabrication methods. The research identified these advancements by investigating startups and businesses that create new products based on an interplay between materials and engineering. The research results show that novel material development crucially requires tradeoffs in material selection, manufacturing processes, engineering design, and product performance. The research findings significantly imply a union between robotics and prosthetics to form the industrial robotics and prosthetics automation market. It was suggested that the development of a material catalogue for prosthetic architecture that presents multidimensional metamaterials contributing to a multidimensional material design space is essential to enable material manipulation with unprecedented attributes for prosthetic architecture. The review proves that multidisciplinary engineering design courses based on human-centered design enable students to acquire prototype design and professional skills. The most recent finding reinforces the difference between artificial intelligence (AI) and intelligence amplification (IA) as it significantly impacts cybernetic organisms, the design of prosthetic architecture, and the future of the sustainable built environment. The case study highlighted some of the ideas that the SLR presented as shown in several drawings above. To expand this research other prosthetic extension possibilities can be explored, such as a School of Architecture Library. Potential further research could include other types of buildings that need a prosthetic for example a hospital needing an additional specialist unit or research centre.

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