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Review of Building Renovation Materials for Structural and Non-Structural Components

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Building renovation materials and strategies have a significant impact on the safety, performance, comfortability, energy efficiency, sustainability, and cost of the building. In this paper, we investigated potential materials for retrofitting both structural and non-structural building components through a comprehensive literature review. The objective of this research is to support decisions for retrofitting building materials. Keywords for the literature review search from the databases include building retrofit, structural retrofit materials, cladding retrofit materials, building renovation. For structural building components, three main categories of renovation materials (the fiber-based, cementitious-based, and metal-based materials) and strategies are reviewed in terms of the mechanical properties and application under extreme loading conditions. Structural retrofitting materials have proven to alter the failure mode of structural members (e.g., from shear failure to flexural failure), increase ductility and energy dissipation capacity, and to improve earthquake and wind performance of the overall structural system. In the case of non-structural building components, we focus our review on renovation materials and strategies applied to building envelope systems. Since structural and non-structural components interact with one another, hybrid solutions including structural and energetic performance using lightweight materials should be considered for the renovation of building envelopes and structural systems.

Key Words: Building retrofit, Materials, Structural components, Non-structural components, Building envelopes

Introduction

Buildings are responsible for more than 40% of the energy use and for one-third of global greenhouse gas emissions (GHG) (Nielsen et al., 2016). Reinforcing and renovating buildings against earthquake damage, wind hazards, and explosive effect of blast is a techno-economic challenge (Raman et al., 2012). Researchers have investigated a broad range of construction materials to retrofit and strengthen building components with the goal of enhancing life-cycle performance and efficiency. Composite materials such as carbon/glass/aramid fibers integrated with polymer matrices are widely used in retrofitting and reinforcing structural components such as columns, beams and masonry walls (Täljsten, 1997). Other common structural retrofitting strategies include reinforced concrete jacketing, steel jacket, and steel plates bonding to retrofit reinforced concrete structures (Cheng et al., 2003; Papanicolaou et al., 2011). At the same time, retrofitting practices of non-structural components that make up the building envelope are focused on enhancing performance measures related to the thermal comfort, energy efficiency and sustainability. In this respect, multidisciplinary approaches in material science, structural analysis, energy innovation, and wind and earthquake engineering should be applied in the building renovation field to seek a holistic performance of building operation. In this paper, we performed a comprehensive literature review to identify traditional and emerging building renovation materials applied to structural and non-structural building components. Advantages and drawbacks of different retrofitting materials and methods are summarized with the goal of supporting future building renovation decisions that consider both structural and non-structural building performance objectives for architectural/engineering/construction community.

Research Methodology

Literature review methods used in this paper included database searches using keywords such as building retrofit, structural retrofit materials, cladding retrofit materials, building renovation. More specific keywords were used to find studies focusing on specific materials or renovation strategies (e.g., fiber-reinforced polymers, shape memory alloys, steel jacketing, etc.). Independent literature searches were conducted to review building retrofit materials for structural and non-structural components. Databases used for the literature review included Google Scholars, Web of Science, and Engineering Village. Additional keywords used in our literature review were discovered by creating a visual network of the top 92 keywords found in studies related to building renovation materials. The network was developed by searching for articles in the Web of Science database that contained the words “building(s)”, “renovation, retrofitting, or rehabilitation”, and “material(s)” in their title, abstract, and author keywords. A total of 1,846 articles were found after limiting (filtering) the search to studies published between 1970-2022. The cluster colors in Figure 1 indicate the strong linkage of words within that cluster. Keywords in the green and blue clusters are associated with structural retrofitting strategies, particularly for reinforced concrete members (e.g., beams, columns, connections, etc.), while the red cluster include keywords related to building envelope performance measures (e.g., thermal insulation, energy efficiency, temperature). Further, the blue cluster suggests that the bulk of structural retrofitting studies have focused on mitigating damage in seismic events.

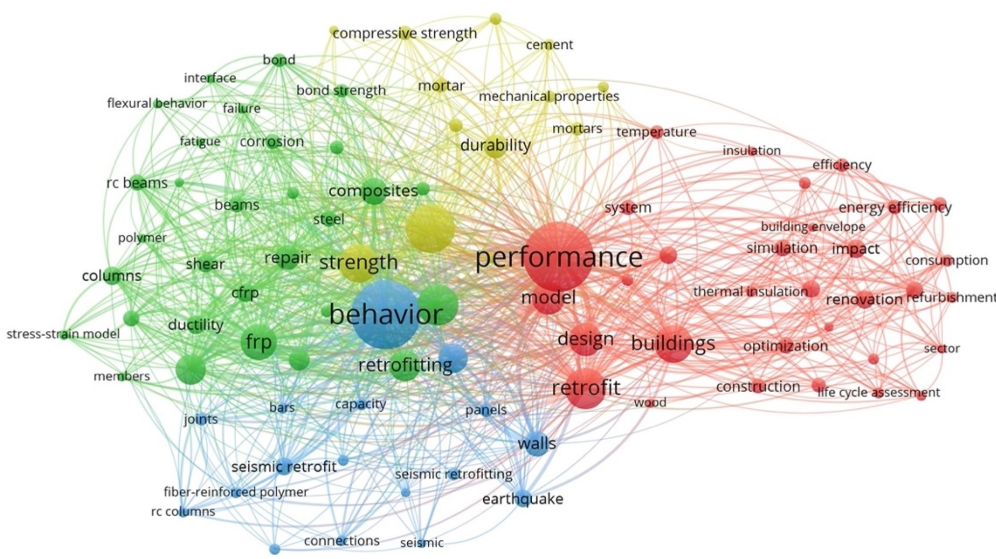

Figure 1. Network of keywords from Web of Science search on building renovation materials.

Building Retrofitting Materials

Structural Components

Modern approach for designing structural building components combines various materials to leverage their unique properties such as mechanical behavior, physical and chemical properties, durability, time-dependent and load-dependent behavior, all the way to the optimized performance of the holistic structure system (Rousakis, 2013). Modern retrofit design codes give recommendations of advanced retrofit materials used for different types of buildings such as the reinforced concrete structures, steel structures, composite structures, and masonry structures (Code, 2010). The following subsections offer a brief review of traditional and recently developed methods and materials used for retrofitting structural building components. Structural renovation materials include: high-performance cement-based materials, fiber-reinforced polymers, shape-memory alloys, and textile-reinforced mortars in the following sections.

Fiber-based Reinforcement Materials

Fiber-based reinforcement materials consist of organic and inorganic fibers. The nonmetallic reinforcing fibers embedded in a polymer matrix are called fiber-reinforced polymers (FRPs). FRP retrofit materials are light, durable and have high strength-to-weight ratios, resulting in economic and technical efficiency compared to traditional techniques. Fibers have high strength and high elastic modulus to transfer loads in the polymer. The matrix has low strength and low elastic modulus, which provide the protection for the fibers from the abrasion and aggressive conditions. Common fibers applied in structural retrofit and strengthening include carbon, glass, aramid, inorganic basalt, polyphenylene benzobisoxazole (PBO), polyethylene naphthalate (PEN), polyethylene terephthalate (PET), thermoplastic fibers including ultrahigh-molecular-weight (UHMW) polyethylene and polyvinyl alcohol (PVA) (Taerwe & Matthys, 2013). Carbon FRP (CFRP), glass FRP (GFRP), aramid FPR, and aramid/glass (A/G) hybrid are commonly used in strengthening structures against blast loads (Raman et al., 2012). Carbon fiber is widely used for the retrofit of the reinforced concrete structure. Its effectiveness lies in the light weight with high strength and good durability. Researchers developed new techniques using carbon fiber to solve for the insufficiency seismic capacity (Billah & Alam, 2014). The smallest unit of carbon fiber is monofilament with the radius 5-15 μm. The practical smallest unit is called strand consisting of 1,000-12,000 monofilaments (Tanaka et al., 1994). The elastic modulus of carbon fiber is similar to the steel while the strength is approximately 10 times that of steel. Glass fiber has high electrical resistance in the structural retrofit and strengthening. Among the common glass fibers, S-glass is stronger and stiffer than E-glass. Aramid fiber, shows good resistance to abrasion, organic solvents, and heat and high elastic modulus. According to the blast experiments on RC walls, A/G hybrid performed better in terms of reducing the residual displacements than CFRP (Muszynski & Purcell, 2003). FRP strengthening materials such as CFRP and E-glass enhanced the performance of RC panels in the ultimate resistance and structural behavior compared to ordinary RC panels (Tolba, 2002). Researchers also investigated that FRP sandwich scheme worked better than single-sided FRP in providing further protection and resisting effects from second explosion (Tanapornraweekit et al., 2010). Elastomeric polymer coating, such as spray-on polyurea-based lines (Knox et al., 2000) was suggested to retrofit the concrete block walls and temporary lightweight buildings by preventing fragmentation from lightweight structural components. Externally bonded grids are applied to retrofit the unreinforced masonry structures. The grids used for the open mesh structures include carbon, glass and basalt fibers and polypropylene or polyester. The bonding agents include mortars of different compositions of epoxy resin (Papanicolaou et al., 2011). Most the FRPs show linear elastic behavior before failure, while PET and PEN show bilinear behavior (Rousakis, 2013). FRP reinforcement completely changed the failure mode of the structures (Colomb et al., 2008). Experimental studies show that the FRPs could (i) change the failure mode from brittle shear failure to bending failure with remarkable ductility capacity (Priestley & Seible, 1995); (ii) increase the maximum load and final displacement; (iii) enhance the lap-splice performance and shear strength; (iv) improve the earthquake resistance capacity.

Cementitious-based Retrofit Materials

The widely used cementitious-based retrofit materials include cast-in-place ordinary concrete, shotcrete or gunite, self-consolidate concrete and fiber-enriched or polymetric mortars (Rousakis, 2013). The materials work as the matrix for reinforcements to retrofit and strengthen the structures or to repair the damaged concrete members. The cementitious-based materials are applied for performance-based solutions. Concrete is a composite heterogenous materials, which consists of cement, sand, gravel and water. The mechanical performance in macroscale level depends on the mechanical properties in microscale level. Microcracks happen at the interface between mortar and gravels even before the loading due to shrinkage, segregation, and thermal expansion in the mortar. The microcracks propagate during the loading from the different stiffness between aggregates and mortar. The crack propagation results in the low tensile strength and the nonlinear behavior of the concrete under loading. Various fiber-reinforced cementitious materials have been developed and applied in structural component retrofit to improve the tensile performance of concrete. These materials include: Ultrahigh-strength fiber-reinforced concrete (UHPFRC), fiber-reinforced cementitious composites (FRCCs). FRCCs have two types: strain-hardening cementitious composite (SHCC) and high-performance fiber-reinforced cement composite (HPFRCC). The high-ductility fiber reinforced cementitious-based materials increase the lateral load-carrying and deformation capacities by replacing the concrete core of the column under seismic loading. The retrofitted structural members such as the concrete columns have better performance in the zone of plastic hinge with better controlled concentrated local damage (Cho et al., 2012).

Metal-based Retrofit Materials

Steel Jacketing. Structural steel has been the primary metal-based material for strengthening existing structural building components, particularly column members and beam-column joints of reinforced concrete frames (Rodriguez & Park, 1991; Wu et al., 2003). The most common structural retrofitting technique is steel jacketing of reinforced concrete columns, where the original structural member is confined in a cage composed of steel angle and plate (or batten) elements (Di Trapani et al., 2021). In contrast to other structural retrofitting approaches (e.g., FRP and concrete jacketing), studies on steel jacketing have shown increased structural performance such as superior shear strength, greater deformation capacity, and enhanced overall ductility of the structural framing system (Villar-Salinas et al., 2021). In particular, steel jacketing is considered to be one of the most efficient methods for increasing ductility of damaged concrete columns (Xiao & Wu, 2003), which makes this approach an attractive alternative for seismic retrofitting. Despite the proven effectiveness of different steel jacketing approaches, some limitations have been documented regarding their reliability when compared to other jacketing materials (e.g., FRP and concrete jackets). For example, minimal enhancement in flexural strength and stiffness has been reported for RC columns with square or rectangular cross-sections, consequently limiting the effectiveness of the method for increasing the deformability of the structural element (Ma et al., 2017). An added disadvantage of steel jacketing is the possibility of premature failure due to debonding and/or peeling of the steel plates along the column-angle contact interface (Campione et al., 2017). Steel plates attached mechanically using anchor bolts may be one alternative to overcome failures associated with debonding, although local buckling of the steel plate under axial or eccentric compression may warrant consideration (Xu et al., 2017).

Shape Memory Alloys. In recent decades, several research studies have explored the suitability of shape memory alloys (SMAs) as a retrofitting material for building structures (Zareie et al., 2020; Zulkifli et al., 2020) given its unique thermomechanical properties. The crystalline structure of SMAs is characterized by two distinct phases (or states), namely martensite or austenite state. The transition from the martensite phase to the austenite phase (upon cooling) is solely dependent on temperature and stress. At lower temperatures (martensite state), SMAs can easily be deformed into any shape. Alternatively, when a SMA is heated, it returns to its pre-deformed (remembered) shape. Further, SMAs can exhibit pseodoelastic behavior (also termed "superelasticy") in which the material can sustain large recoverable strains with little to no permanent deformation. High fatigue strength during inelastic cyclic loading and relatively good resistance to corrosive agents are other attractive characteristics of SMAs for civil engineering applications, particularly for seismic retrofitting of structures (Hojatirad & Naderpour, 2021). The two most widely used SMAs are copper-aluminum-nickel and nickel-titanium (NiTi), but SMAs can also be generated by alloying zinc, copper, gold and iron. SMAs have proven effective when used as passive structural control devices in buildings to dissipate (dampen) vibration energy induced by extreme loading (Zareie et al., 2020). Specifically, steel braces equipped with martensite or austenite SMA elements have been tested and integrated into lateral load resisting systems of multi-story frames to enhance energy dissipation under seismic loads (Gao et al., 2016; Speicher et al., 2017; Qiu et al., 2020). SMAs have also been successfully applied to other structural components such as RC and masonry walls (Rezapour et al., 2021) and RC T-beams (Cladera et al., 2020) and beam-column joints (Hojatirad & Naderpour, 2021).

Non-Structural Components

Among diverse building retrofit such as roof, façade, HVAC, etc. (Li & Chen, 2020) building envelope is one of significant elements in renovation process in terms of it impacts the appearance (Tovarović et al., 2017), external surface temperature (Cronhjort, 2011), and building energy consumption (Chang et al., 2020). Multiple objectives such as cost, energy, comfort, and CO_2 emissions have been considered to provide adequate building envelope retrofit options (Chang et al., 2020). To increase energy efficiency of existing buildings, double skin façade (DSF) (Gelesz & Reith, 2015), double and triple glazed low-e glass (Eskin & Türkmen, 2008), biomass façade (Chang et al., 2017), laminated glass integrated with LED technology, installation of the brise soleil solar shading system (Tovarović et al., 2017), and integration of photovoltaic modules (Chang et al., 2021; Quan et al., 2015) have been studied. However, wind performance of building envelopes has often been overlooked so that inadequate design attention has limited wind resistance (Smith, 2017). As a result, windborne facade debris that can easily penetrate wall coverings has threatened indoor environment quality as well as outdoor pedestrian's safety. Damage to non-structural components causes economic losses as well as threats to life safety (Sousa & Monteiro, 2018).

Non-load bearing walls (non-structural envelope components) should be able to resist the positive and negative wind loads for screening rain / water by equalizing pressure and avoiding windborne envelope debris. Most of the cladding damage was caused by lack of hurricane-resistant construction, resulting in poor connections between cladding components and the main structural system (either by design or loss of strength due to corrosion) (Kareem, 1986). In high-wind areas, for exterior fenestration, laminated glazing that is bonding layers of float glass with plasticized polyvinyl butyral (PVB resin or polycarbonate (PC) resin can withstand high pressure (Spence & Kultermann, 2016). Laminated glass, composed by glass plies, can be used for structural purposes because it will attach to the interlayer even after the glass breaks and provide a residual load-bearing capacity (D'Ambrosio et al., 2019). Thus, the retrofit option of laminated glass will transform the use of glass being both non-structural and structural applications while providing transparent envelopes (Machado-e-Costa et al.,

2016) have been studied. For retrofitting exterior opaque envelopes, a variety of materials have been studied for building renovation including Vacuum insulation panels (VIPs), Trombe walls, Phase Change Materials (PCM), etc. (Chang, 2020). For example, wood materials were considered as substitution of carbon-intensive materials based on life cycle carbon balance (Piccardo et al., 2020). Vacuum insulation panels (VIPs) with fiber felt/silica aerogel composite cores, one of energy efficient insulation materials, were studied to improve the thermal performance and the service life over 50 years (Liang et al., 2017). VIPs consist of inner core, multilayer envelopes, and getters and desiccants (Alam et al., 2011). The multilayer envelope can be either thick metal sheets or lighter multilayered metalized polymer file for protecting environmental and handling stresses (Alam et al., 2011). Trombe wall systems can reduce heating energy load by utilizing solar radiation but need additional insulation for summer to prevent undesirable overheating (Jaber & Ajib, 2011). In addition, phase change materials (PCM) can be applied to both the glass curtain wall system (Park et al., 2019) and the opaque envelope (Cascone et al., 2018) as a passive retrofit strategy for saving energy by utilizing optimal thermophysical properties in given weather conditions. Unreinforced brick masonry walls, one of non-structural retrofitting materials, have also been analyzed for achieving seismic performance and cost benefits (Sousa & Monteiro, 2018).

Meanwhile, extensive studies have found that exterior non-structural wall coverings not only directly interact with the structural system (Sousa & Monteiro, 2018) but also are vulnerable to damages under external loads such as wind and earthquake, etc. (Cardone et al., 2019). Therefore, to achieve sustainability including environment, economy, and society (in this research, the bearability under multiple wind hazards), a hybrid structural-plus-energy retrofitting solution based on innovative lightweight materials (Bournas, 2018) should be reviewed and applied for both wind load resistance and energy efficiency. In this respect, new composite materials such as cotton/polyester blend, SEBS (styrene–ethylene–butylene–styrene) -Biotex, PTFE (polytetrafluoroethylene)-fiber glass fabric, and SEBS-carbon fiber fabric have proposed to increase economic and environmental sustainability while enabling a lightweight load-bearing feature (Rodonò et al., 2019).

Conclusion

Building renovation materials play a significant role in the overall performance of building systems. A holistic assessment to identify the best building renovation practices requires a multidisciplinary approach that combines both structural and non-structural performance objectives related with structural safety, thermal comfort, energy efficiency and cost. In this study, we reviewed recent advances in building renovation materials and strategies for both structural and non-structural components, independently. In the renovation of structural components, different building materials (e.g., fiber-based polymers, cement-based, SMAs) and retrofitting techniques have proven effective in enhancing structural performance under to extreme loading conditions. However, the literature review indicates that the bulk of these approaches centered around seismic events and research on structural retrofitting strategies for other types of natural hazards (e.g., windstorms) is currently scarce (or absent) in literature. Conversely, renovation methods for non-structural components that make up the building envelope must provide adequate strength to resist extreme wind pressures that act on the exterior building façade. Additionally, the prevention of water intrusion from wind-driven rain is also a critical factor when assessing and improving building envelope performance. It is noted that both structural and non-structural components are integrated within building systems and their performance measures are distinctively different from one another. Therefore, multi-objective strategies should be implemented to clearly map competing objectives between both components when seeking the most adequate retrofitting material and approach.

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