A review on concrete-filled steel hollow column subjected to fire and cyclic loadings

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Abstract. Concrete-filled hollow steel column (CFHS) column is a composite column that comprised of concrete core filled into hollow steel section. The composite action between the hollow steel sections and concrete core give CFHS better performance over conventional reinforced concrete and steel column. Numbers of studies had been done on the performances of CFHS with different types of the concrete core subjected to various loadings. The concrete filling materials used by previous researchers including plain concrete, reinforced concrete, and other modified concrete such as concrete containing fly ash, recycled aggregate and rubber particles. This paper presents the performances of CFHS with different type of concrete filling materials subjected to fire and cyclic loadings. A comparison between different concrete filling materials that have been used to fill hollow steel column that were used by previous researchers are presented. Research gap and recommendations are also proposed for further study.

Keywords: hollow steel column, concrete filling, fire loading, cyclic loading, bearing capacity

1. Introduction

The application of steel-concrete composite column has become more popular due to the benefits in terms of mechanical behaviour and construction properties over plain concrete and reinforce concrete [1–8]. Concrete-filled hollow steel (CFHS) column with normal concrete as filling material is not something new to the construction industry. China is one of the country countries that have conducted a great deal of research on concrete-filled hollow steel and application in their practices [9]. China has used elliptic short column with normal concrete as filling material for experimental study [10]–[12]. Commonly, CFHS is widely used in component installation for large span, tower and heavy load such as bridge, high-rise building and other heavy load structure, thus tendency for these structures to experience cyclic loading is high. The structures that had utilised CFHS include Canton Tower (China), Taipei 101 Tower (Taiwan) and Ganhaizi Bridge (China).

Hollow steel column are widely used in steel structure construction owing to their high strength, ductility and light weight, and can be found in cold form steel and hot rolled steel section. As for elevated temperature, although steel is not burning material, it has poor fire resistance due to high
thermal conductivity characteristic, thus able to transfer heat faster compared to concrete with low thermal conductivity and good insulating material. Hence, introduction of concrete filler can give flexural effect to the hollow steel column (HSC), while HSC can give confinement effect to the concrete in order to improve column performances when subjected to fire and cyclic loading.

In general, studies have been conducted focusing on normal concrete that used Ordinary Portland Cement (OPC) as filling material in CFHS. However, as the trend in construction field is moving towards sustainable development, carbon emission through the usage of OPC has been debated by researchers. Thus, modification of the ordinary cement by replacing certain percentage of OPC with waste pozzolanic material- fly ash, slag, and rice husk ash can be considered as solution to reduce the carbon emission by the production of OPC. As there are additional replacement materials in the modified cement, the properties of concrete will also change depending on the type of material used. Thus, the performances of CFHS with different filling material under fire and cyclic loading will vary according to type of cement used in the concrete infill. For example, the performances of pozzolanic-fly ash concrete-filled hollow steel column is believed to improve column performances during fire and seismic event as fly ash has good pozzolanic reaction during high temperature, and improved energy dissipation capability of steel column under cyclic loading.

The replacement of natural aggregates in concrete with green materials is also a step for sustainable development in construction field. Rubber particles is popular in construction of road pavement, and further studies have been conducted by researchers on the utilisation of rubber particles in concrete for structural application. Rubberized concrete can improve concrete performances during cyclic loading due to elastic behaviour of rubber particles, and thus can improve the behaviour of concrete-filled hollow steel (CFHS) column under seismic loads. Research on CFHS with rubberized concrete is not significant to be done under fire event as the strength of rubberized concrete is lower as compared to normal concrete. This paper will briefly discuss the performances of CFHS with normal concrete, pozzolanic-fly ash concrete and rubberized concrete when subjected to fire loading and cyclic loading.

2. Concrete

2.1 Normal Concrete

It is a point of fact that Ordinary Portland cement (OPC) is one of the most consumed materials in the construction industry due to availability in specified country and has been used as the main binding material in construction industries across the globe. OPC mixed with water and aggregate will form ubiquitous concrete including become filling material for hollow steel column. The study on concrete filled hollow steel column is actively investigated especially in countries exposed to earthquake, such as China. This is because flexible elements like hollow steel column are commonly used in high-rise building, where there is high probability of fire to occur after earthquake event.

2.2 Pozzolanic Concrete

Pozzolanic materials or pozzolans are materials containing reactive silica, which in themselves possess little or no cementitious properties, in which and in the presence of water and react chemically with calcium hydroxide producing cementing properties. Pozzolanic material can be divided into two categories, natural pozzolans such as volcanic ash, and artificial pozzolans such as fly ash, ground blast furnace slag and rice husk ash. Pozzolans are normally used as supplementary cementing materials in Portland cement.

Pozzolanic concrete is combination of OPC with pozzolans at specified ratio. Many researchers believe that by using pozzolanic concrete, emission of CO$_2$ can be reduced, which can reduce effect on global warming. Thus to reduce consumption and dependency on cement, utilization of pozzolanic materials such as ground granulated blast furnace slag, palm oil fuel ash (POFA), and rice husk ash (RHA), fly ash, silica fume, etc. as supplementary cementing materials has become the leading research interest in the area of cement and materials research in recent decades. Figure 1 shows the sample of fly ash been used as building material for high rise building [13].
2.3 Rubberized Concrete
Recycling of waste tires is a way to overcome the problems with waste tires. The most preferred method for the recycling of tire rubber is by grinding it and then to converting it for various applications. Crumb rubber is produced through re-processing (shredding) disposed automobile tires [14]. Shredding waste tires and removing wire beads found in steel-belted tires generates crumb rubber. Crumb rubber is widely used in various applications such as turf fields, playgrounds, asphalt and many more. The crumb rubber used in concrete or asphalt paving mixtures is in sizes ranging from 0.0075mm to 4.75 mm [15]. Ganjian et al. [16] have classified the recycled tire rubber into chipped rubber replacing coarse aggregates, crumb rubber replacing fine aggregates and ground rubber replacing partial amount of cement, as shown in figure 2. In general, rubberized concrete is same as normal concrete, which is made of cement, fine and coarse aggregates, and water. The only difference in the concrete mix is the partial replacement of natural aggregates with rubber particles.

![Figure 2](image)

**Figure 2.** Different type of recycled tire rubber (a) Crushed Rubber (waste tire chips), (b) Crumb rubber, and (c) Ground Rubber [17], [18]

3. Performance of CFHS subjected Fire Loading with Different Filling Materials
Fire resistance is the duration of the passive fire protection system that can withstand fire loading for specified element. This can be quantified simply by measuring the time taken for the element to fail when subjected to fire loading. Commonly, fire resistance of the element differs based on thermal properties of the specified element used. In addition, thermal properties that are usually highlighted during fire testing is thermal conductivity, which is the rate at which heat passes through the material. For example, steel column has higher thermal conductivity as compared to concrete column. Table 2 shows the thermal conductivity of some commons material used in construction industry. Among these materials, steel column has highest thermal conductivity as compared to the others materials.
Table 1. Show the thermal conductivity of construction material [13]

| Material | Thermal conductivity (W/ (m.K)) |
|----------|---------------------------------|
| Steel    | 45                              |
| Concrete | 1.13                            |
| Timber   | 0.14                            |
| Brick    | 0.73                            |

3.1 Normal Concrete
Filling OPC into hollow steel column can reduce thermal conductivity of the column so that the duration of column to fail during high temperature will increase. In addition, the use of OPC can improve compression strength and flexural stiffness of the section, thus preventing or avoiding buckling of the steel tube [19], [20]. In contrast, steel tube can give confinement effect to the concrete, thereby improving the strength and preventing sapling that might occur in conventional reinforce concrete [12], [20]–[23].

In fact, the production of OPC is responsible for the impact to the environment due to the release of many harmful gasses such as carbon dioxide (CO2), which lead to problems like greenhouse effect and global warming, a topic that has been debated frequently [19], [24], [25]. Thus, a solution proposed by researchers is the conversion of OPC to pozzolanic concrete by replacing about 15% to 30% of OPC with pozzolan such fly ash.

3.2 Pozzolanic Concrete
A large number of researches have focused on the utilization of waste material in concrete and thus, for construction industry, the use of blended cement with pozzolanic material has grown rapidly [24], [26]. Therefore, the use of pozzolanic material such as fly ash, silica flour and RHA have attracted increased attention as they can improve the properties of the mixture [19], [27]. In recent years, pozzolanic material, also known as pozzolan, is produced from waste material that has been dumped in landfills. Thus, various studies have been conducted with a focus on the utilization of by-product as an alternative in order to increase mechanical properties of OPC [19]. There are six (6) types of material from by-product that have been used in Pozzolanic Cement (CEM II) - slag, pozzolan, silica fume, fly ash, burnt shale and limestone. Of these, fly ash is the most popular pozzolan used in industry.

Fly ash is a by-product of coal combustion at coal-fired power generation plants. The pozzolanic property of fly ash makes it a resource for making cement and other ash based products. Table 1 shows the chemical composition of fly ash. In 2013, it was recorded that Malaysia had produced more than 54 million metric tons of the FA and only 23 million metric tons (42.6% of the total FA) was used. The remainder, or 57.2% of the total produced FA, were disposed in landfills [28]. In 2016, Tanjung Bin coal-fired power plant generated about 50,000 metric tonnes of fly ash monthly, and this product was sold to cement producers to produce blended cement [29].

Table 2. Chemical composition of class C and class F fly ash in Malaysia [28]

| Chemical composition of FA | SiO² | Fe₂O₃ | Al₂O₃ | CaO | K₂O | Na₂Oₑq | SO₃ | MgO | LOI |
|---------------------------|------|-------|-------|-----|-----|--------|-----|-----|-----|
| Class C                   | 20.7 | 32.0  | 9.01  | 27.1| 2.51| 1.00   | 1.61| 2.05| 2.97|
| Class F                   | 55.23| 10.17 | 25.95 | 1.32| 1.59| 1.59   | 0.18| 0.31| 5.25|

Using pozzolanic material involves alkaline activation and sulphate activation. Fly ash has low initial activation on alkaline, which will decrease the heat hydration compared to silica fume, which produces high heat during cement hydration [25]. Thus, the study is focusing on fly ash as it is proven
that it can solve the problem of production of high heat. Figure 3 shows the graph of compressive strength concrete with OPC (FA0) and replacement of 30% of OPC with pozzolanic material, which is fly ash (FA30). As shown, compressive strength of fly ash concrete is higher as compared to OPC concrete at elevated temperature.

![Figure 3. Chemical composition of class C and class F fly ash in Malaysia [24]](image)

4. Performance of CFHS subjected Cyclic Loading with Different Filling Materials

Earthquakes can cause disasters including damage or collapse of buildings and other man-made structures. Structural design is to ensure that buildings have adequate strength, high ductility and can remain as a unit after subjected to large deformation during a seismic event. Seismic-resistant structures offer better performance when subjected to seismic actions by minimizing or eliminate structural damages, and can prevent collapse of structures.

Concrete-filled hollow steel (CFHS) column has been increasingly used in construction fields, including high-rise buildings and bridges [30]–[32]. It is a type of composite steel-concrete structural member, where concrete is filled into hollow steel section. Steel is known for high tensile strength and ductility, while concrete is good in compressive strength and stiffness [33]. The combination of composites of both elements contribute to improvement of overall performance of the column including sufficient strength, ductility and stiffness [34]. The hollow steel section act as permanent formwork and provides confinement to the concrete infill, enhancing strength of column, while concrete core delays the local buckling of the hollow steel section [35]. From structural point of view, concrete core of CFHS has the capability to delay local buckling of hollow steel section that increase the ductility and energy dissipation of the member, resulting in improved seismic performance in comparison to reinforced concrete and steel section elements [36].

As concrete-filled hollow steel column consist of two different materials (hollow steel section and concrete), the behaviour of CFHS under loading, including cyclic loads, depends on the properties of the two materials. Thus, concrete core as one of the main components plays an important role in the performance of CFHS under cyclic loading. The parameters of concrete including type of concrete, concrete grades, type of cement, aggregate, design mix etc. will determine the behaviour of CFHS. Number of researches has been done on different type of concrete infill in CFHS column such as normal concrete, recycled aggregate concrete, and rubberized concrete when subjected to cyclic loads, and are discussed in next subchapter.
4.1 Normal Concrete
Elremaily and Azizinamini [33] studied the cyclic behaviour of circular concrete-filled hollow steel (CFHS) columns. The results showed that CFHC exhibited high ductility and energy-dissipation capability. The confinement effect of the hollow steel column increased concrete strength, improving the capacity of the column. The slenderest columns ($D/t = 51$) have lower energy dissipation capacity by 33% compared to stockier columns ($D/t = 34$). Fam et al. [37] have conducted similar test with constant $D/t$ ratio of 49 and different bond type between concrete infill and hollow steel section. Same conclusion is obtained where column specimens exhibit high ductility with bonded CFHS column having higher stiffness compared to unbonded one. It is found that the available design specifications, Canadian, American, and Japanese, were too conservative and underestimated the capacity of CFST columns due to the absence of concrete confinement and steel tube hardening effects.

Han et al. [38] had studied the flexural behaviour of concrete-filled thin-walled steel square hollow section (SHS) and rectangular hollow section (RHS) beam-columns tested under constant axial load and cyclically increasing flexural loading. Results showed that the ductility of columns decreases with the increase of depth-to-width ratio, concrete compressive strength and axial load level.

An experiment on behaviour of partially concrete-filled steel tube (PCFST) bridge piers under bi-directional seismic excitation was conducted by Yuan et al. [39]. The testing was carried out on circular section specimens with different concrete-filled ratios (0%, 25% and 50% of column height), under a series of cyclic static loading tests, and single- and bi-directional hybrid (pseudodynamic) loading tests. The test result for the three types of infill ration is shown in figure 4. Testing results concluded that filled-in concrete improved the seismic behaviour of steel bridge piers under single- or bi-directional seismic loads compared to bare steel bridge piers, in which higher level of concrete infilled has better performance under seismic loads. In comparison with specimen without concrete infill, the lateral displacement of specimens with concrete fill heights of 25% and 50% of column height increased by approximately 29% and 44%, respectively, thus showing better deformation capacity due to the encased concrete prevented buckling deflection of the outer steel plates of the cross section.

![Figure 4](image)

**Figure 4.** Test results of static cyclic loading tests (a) concrete-filled ratio 0%, (b) concrete-filled ratio 25%, (c) concrete-filled ratio 50%, [39].

4.2 Pozzolanic Concrete
Arivalagan and Kandasamy had carried out study on concrete filled steel hollow beam with normal concrete and pozzolanic concrete subjected to seismic load [40]. The author conclude that concrete...
filled rectangular hollow steel (RHS) beam have higher moment capacity as compared to bare rectangular hollow steel beam. Results indicated that the increase in ultimate moment capacity was found to be about 20% to 28% for RHS filled with pozzolanic concrete (fly ash). In addition, the increase in energy absorption capacity in rectangular section filled with fly ash concrete is 1.49 when compared to hollow section. It can be concluded that by filling steel hollow section with concrete mix can improve performances of the element because of confinement effect from steel hollow section and flexural strength from concrete in-filled. Figure 5 shows the Moment-Strain hysteric loop curve of Pozzolanic – Fly ash Concrete and Normal Concrete, indicating that a uniform mechanism without cracking was observed.

![Figure 5. Moment-Strain hysteric loop curve](a) Fly ash Concrete Filled Rectangular Hollow Steel, (b) Rectangular Hollow Steel Column [40].

### 4.3 Rubberized Concrete

Rubberized concrete is one of the green concrete that have utilized rubber particles from waste tires as partial natural aggregates replacement. Studies have been done on the performance of rubberized concrete subjected to cyclic loading. Zheng et al. [41] observed improvement in damping ratio of rubberized concrete compared to normal concrete. The damping ratio increased considerably with increase of rubber content and optimal rubber content of less than 30% is suggested for satisfactory dynamic properties. Atahan and Yücel [42] studied the usage of rubber particles in concrete safety barrier and highlighted that the energy dissipated by rubberized concrete increase drastically as rubber content increase. Xue and Shinozuka [43] studied the static and dynamic performance of rubberized concrete column specimens. It was observed that the damping coefficient of the rubberized concrete column increased by 62% compared with normal concrete and as a result, the seismic response acceleration of the column structure decreased by 27%. Zukri [44] studied the performance of waste crumb rubber steel fibre concrete under dynamic loadings. Results showed that the presence of treated crumb rubber and steel fibre in concrete mixture helps in reducing seismic force by delaying the propagation of crack and improving the stiffness of concrete column. Due to good dynamic performance of rubberized concrete, further study has been carried out on the behaviour of rubberized concrete as infill materials in concrete-filled hollow steel (CFHS) when subjected to seismic load.

Duarte et al. [45] studied the cyclic behaviour of rubberized concrete-filled hollow steel column with partial replacement of natural coarse aggregates with rubber particles for the concrete infill. The authors concluded that circular section is two times more ductile compared to square and rectangular section. Increasing the rubber particle content from 0 to 15% leads to a decrease of the cyclic strength and stiffness of the columns due to the lower compressive strength and Young’s modulus of concrete with higher rubber content. Considering the influence of the concrete’s core mix on the ductility of the
columns, 5% rubberized concrete provides the highest ductility of CFST columns, with increases reaching about 50% of normal concrete. Even though 15% rubberized concrete is more ductile than 5% rubberized concrete, the fact is that 15% rubberized concrete increases the column sensitivity to local buckling due its lower stiffness and strength. Thus the authors conclude that concrete mix with a low replacement ratio (5%) of natural aggregates with tire rubber aggregates is the most suitable to be used in CFHS for seismic area due to the lowest decrease in the maximum lateral load and the highest increase in the ductility of column.

Silva et al. [36] investigated the flexural behaviour of circular rubberized concrete-filled hollow steel column with 5% (RuC5%) and 15% (RuC15%) replacement ratio of coarse aggregate with rubber particles compared with normal concrete. Circular concrete-filled hollow steel (CFHS) and rubberized concrete-filled hollow steel (RuCFHS) specimens exhibited a very ductile behaviour under both monotonic and cyclic loading upon experimental testing. The authors concluded that concrete type does not give significant effect on specimen behaviour under monotonic and cyclic lateral loading. The decrease in maximum lateral force of RuC5% specimens as compared to normal concrete is about to 7%, while the decrease for RuC15% ranges from 4.4 to 11.5%. The cyclic test results are shown in figure 6. These observations denote that concrete infill type gives minor influence on member behaviour and the flexural strength of the member is largely dominated by the contribution of the steel tube.

![Figure 6](attachment:image.png)

**Figure 6.** Cyclic test results of specimens (a) Axial load level, n = 0%, (b) Axial load level, n = 15%

5. Conclusion
Current trend of construction industry is toward sustainable development and this includes utilisation of green materials including pozzolanic materials such as fly ash, ground blast furnace slag and rice husk ash, and possible natural aggregates substitution such as waste tire rubber particles. The applications of the green materials in concrete for structural application are being continuously studied including the behaviour of the members under fire and cyclic loadings.
In terms of fire, application of pozzolanic concrete as concrete infill for CFHS is new to research field, hence, performances of CFHS with pozzolanic concrete require further attention to achieve sustainable development in construction industry. In structural field, rubber particles in concrete are known to have good performance of seismic resistant properties as stated by previous researches [41]–[44]. However, there are still gaps in research on the application of rubberized concrete as infill of CFHS, especially the utilisation of crumb rubber replacing fine aggregates in the concrete core. Furthermore, the improvement of CFHS with utilization of the combination between rubber particles and pozzolanic materials in concrete core requires further study. Over the past years, many researches have been conducted on the behaviour of concrete-filled hollow steel columns under different types of loading. A wide range of studies has been done on behaviour of concrete-filled hollow steel (CFHS) columns with different hollow steel section parameters, concrete parameters and loading conditions. Based on previous researches, it is shown that CFHS columns have many advantages over normal steel and reinforced concrete and have been applied in buildings construction including high-rise building and bridges. As sustainability is currently a major concern, further works and improvements are needed to determine the suitability and advantages that can be provided by green materials in concrete core of CFHS columns, especially when subjected to fire and cyclic loadings.

6. References
[1] Espinos A, Romero M L, Serra E, and Hospitaler A 2015 Experimental Investigation On The Fire Behaviour Of Rectangular And Elliptical Slender Concrete-Filled Tubular Columns Thin-Walled Struct. 93 137–148.
[2] Espinos A, Romero M L, Serra E, and Hospitaler A 2015 Circular And Square Slender Concrete-Filled Tubular Columns Under Large Eccentricities And Fire J. Constr. Steel Res. 110 pp.90–100.
[3] Wan C Y, Zha X X, and Dassekpo J B M 2017 Analysis of axially loaded concrete filled circular hollow double steel tubular columns exposed to fire Fire Saf. J. vol. 88 pp. 1–12.
[4] Shekastehband B, Taromi A, and Abedi K 2017 Fire performance of stiffened concrete filled double skin steel tubular columns Fire Saf. J. 88 pp. 13–25.
[5] Wang H, Zha X, Liu Y, Luo C, and Lu C K 2017 Study of recycled concrete–filled steel tubular columns on the compressive capacity and fire resistance Adv. Mech. Eng. 9 no. 6, p. 168781401770506.
[6] Du Y, Chen Z, Richard L J Y, and Xiong M X 2017 Rectangular concrete-filled steel tubular beam-columns using high-strength steel: Experiments and design J. Constr. Steel Res. 131 pp. 1–18.
[7] Lie T T and Chabot M 1992 Experimental Studies on the Fire Resistance of Hollow Steel Columns Filled with Plain Concrete Natl. Res. Coun. Canada 611.
[8] Tao Z, Hassan M K, Song T Y and Han L H 2017 Experimental study on blind bolted connections to concrete-filled stainless steel columns J. Constr. Steel Res. 128 pp. 825–838.
[9] Han L H, Li W and Bjorhovde R 2014 Developments and advanced applications of concrete-filled steel tubular (CFST) structures: Members J. Constr. Steel Res. 100 pp. 211–228.
[10] Fan S, Chen G, Xia X, Ding Z and Liu M 2016 Fire resistance of stainless steel beams with rectangular hollow section: Numerical investigation and design Fire Saf. J. 79 pp. 69–90.
[11] Kesawan S and Mahendran M 2018 Post-fire mechanical properties of cold-formed steel hollow sections,” Constr. Build. Material. 161 pp. 26–36.
[12] Liu F, Gardner L and Yang H 2014 Post-fire behaviour of reinforced concrete stub columns confined by circular steel tubes,” J. Constr. Steel Res. 102 pp. 82–103.
[13] Thomas M D A 2007 Optimizing the Use of Fly Ash in Concrete Portl. Cem. Assoc. p. 24.
[14] Chesner W, Collins R and MacKay M 1998 Users guidelines for waste and byproduct materials in pavement construction.
[15] Thomas B S and Gupta R C 2016 A comprehensive review on the applications of waste tire rubber in cement concrete Renew. Sustain. Energy Rev. 54 pp. 1323–1333.

[16] Ganjjan E, Khorami M and Maghsoudi A A 2009 Scrap-tyre-rubber replacement for aggregate and filler in concrete Constr. Build. Mater. 23 no. 5 pp. 1828–1836.

[17] Kang J, Zhang B and Li G 2012 The abrasion-resistance investigation of rubberized concrete J. Wuhan Univ. Technol. Mater. Sci. Ed. 27 no. 6 pp. 1144–1148.

[18] Li L, Ruan S and Zeng L 2014 Mechanical properties and constitutive equations of concrete containing a low volume of tire rubber particles Constr. Build. Mater. 70 pp. 291–308.

[19] Mehta A and Siddique R 2017 Properties of low-calcium fly ash based geopolymer concrete incorporating OPC as partial replacement of fly ash Constr. Build. Mater. 150 pp. 792–807.

[20] Bagherinejad K, Hosseinpour E and Hosseini S H 2015 Evaluation of Rectangular Concrete-Filled Steel-Hollow Section Beam-Columns J. Asian Sci. Res. 5 no. 1 pp. 46–59.

[21] Sheehan T, Dai X H, Chan T M, and Lam D 2012 Structural response of concrete-filled elliptical steel hollow sections under eccentric compression Eng. Struct. 45 pp. 314–323.

[22] Wang Y, Chen J and Geng Y 2015 Testing and analysis of axially loaded normal-strength recycled aggregate concrete filled steel tubular stub columns Eng. Struct. 86 pp. 192–212.

[23] Wang Y, Chen P, Liu C and Zhang Y 2017 Size effect of circular concrete-filled steel tubular short columns subjected to axial compression Thin-Walled Struct. 120 pp. 397–407.

[24] Chindaprasirt P, Rukzon S and Sirivivatnanon V 2008 Resistance to chloride penetration of blended t Portland cemen mortar containing palm oil fuel ash, rice husk ash and fly ash Constr. Build. Mater. 22 no. 5 pp. 932–938.

[25] Li G 2004 Properties of high-volume fly ash concrete incorporating nano-SiO 2 Cem. Concr. Res. 34 no. 6 pp.1043–1049.

[26] Chindaprasirt P and Rukzon S 2008 Strength, porosity and corrosion resistance of ternary blend Portland cement, rice husk ash and fly ash mortar Constr. Build. Mater. 22 no. 8 pp. 1601–1606.

[27] Abubakar A U and Baharudin K S 2012 Potential Use of Malaysian Thermal Power Plants Coal Bottom Ash in Construction Int. J. Sustain. Constr. Eng. Technol. 3 no. 2 pp. 2180–3242.

[28] Fauzi A, Nuruddin M F, Malkawi A B and Abdullah M M A B 2016 Study of Fly Ash Characterization as a Cementitious Material Procedia Eng. 148 pp. 487–493.

[29] Malakoff Corporation Berhad 2016 Malakoff Corporation Berhad Annual Report 2016.

[30] Sankar J J S and Jayalekshmi S 2014 Advancements in Concrete Filled Steel Tubular (CFST) Columns - a Review Int. J. Struct. Civ. Eng. Res. 3 no. 2 pp. 57–64.

[31] Wagh M M and Mohod M V 2015 A Review on Concrete Filled Steel Tubes Column Int. J. Res. Eng. Sci. Technol. 1 no. 8.

[32] Ezoji R 2017 A review on behaviour and strength of concrete filled steel tubular columns J. Civ. Eng. Res. 1 no. 7 pp. 12–16.

[33] Elremaily A and Azizinamini A 2002 Behavior and strength of circular concrete-filled tube columns J. Constr. Steel Res. 58 no. 12 pp. 1567–1591.

[34] Hatzigeorgiou G D and Beskos D E 2005 Minimum cost design of fibre-reinforced concrete-filled steel tubular columns J. Constr. Steel Res. 61 no. 2 pp. 167–182.

[35] Abendeh R, Ahmad H S and Hunaiti Y M 2016 Experimental studies on the behavior of concrete-filled steel tubes incorporating crumb rubber J. Constr. Steel Res. 122 pp. 2051–260.

[36] Silva A, Jiang Y, Castro J M, Silvestre N and Monteiro R 2016 Experimental assessment of the flexural behaviour of circular rubberized concrete- filled steel tubes 122 pp. 557–570.

[37] Fam A, Qie F S and Rizkalla S 2004 Concrete-Filled Steel Tubes Subjected to Axial Compression and Lateral Cyclic Loads J. Struct. Eng. 130 no. 4 pp. 631–640.

[38] Han L H, Yang Y F and Tao Z 2003 Concrete-filled thin-walled steel SHS and RHS beam-columns subjected to cyclic loading Thin-Walled Struct. 41 no. 9 pp. 801–833.
[39] Yuan H, Dang J and Aoki T 2014 Behavior of partially concrete-filled steel tube bridge piers under bi-directional seismic excitations J. Constr. Steel Res. 93 pp. 44–54.
[40] Arivalagan S and Kandasamy S 2010 Study on Concrete–Filled Steel Member Subjected to Cyclic Loading Int. J. Civ. Struct. Eng. 1 no. 3 pp. 458–465.
[41] Zheng L, Huo X S and Yuan Y 2008 Experimental investigation on dynamic properties of rubberized concrete 22 pp. 939–947.
[42] Atahan A O and Yücel A Ö 2012 Crumb rubber in concrete: Static and dynamic evaluation,” Constr. Build. Mater. 36 pp. 617–622.
[43] Xue J and Shinozuka M 2013 Rubberized concrete: A green structural material with enhanced energy-dissipatiocapability Constr. Build. Mater. 42 pp. 196–204.
[44] Zukri S N N M 2017 Performance Of Waste Crumb Rubber Steel Fiber Concrete Under Dynamic Loadings 2017.
[45] Duarte A P C, Silva B A Silvestre N, Brito J D, Júlio E and Castro J M 2016 Experimental study on short rubberized concrete-filled steel tubes under cyclic loading Compos. Struct. 136 pp. 394–404.

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