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Self-Compacting-Geopolymer-Concrete (SCGC) Retrofitted Haunch

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Abstract

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the SCGC haunch reduced the deflection at mid-span to 77%.

Keywords

Haunch; Plastic-Hinge; Retrofitting; Self-Compacting Geopolymer Concrete (SCGC)

Refbacks

There are currently no refbacks.

Self-Compacting-Geopolymer-Concrete (*SCGC*) Retrofitted Haunch

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Keywords: *Haunch, Plastic-hinge, Retrofitting, Self-Compacting Geopolymer Concrete (SCGC)*

Nomenclature

AA	Alkaline activator
AASHTO	American Association of State Highway and Transportation Officials standard
ACI	American Concrete Institute standard
ASTM	American standard testing and material
d_b	Longitudinal reinforcement diameter (mm)
E	Modulus of elasticity (MPa)
EDX	Energy dispersive X-ray
EFNARC	European SCC specifications and guidelines
f'_c	Concrete's cylinder compressive strength (MPa)
FA	Fly ash
f_{MR}	Concrete's flexure tensile strength (MPa)
f_{tr}	Concrete's split cylinder tensile strength (MPa)
FRP	Fiber-reinforced polymers
h_c	Column depth (mm)
h_h	Haunch depth (mm)
I	Section moment of inertia (mm^4)
L	Beam length (mm)
$L_{original}$	Prismatic beam clear span (mm)
L_{haunch}	Haunch beam clear span (mm)
LVDT	Linear variable differential transformers
M_{FEM}	Fixed end moment (N-mm)
M_{ij}	Actual joint moment (N-mm)
M_i	Actual moment distance at a distance x from the beam-column joint (N-mm)
q	Uniform load (kg/m^2)
SCGC	Self-compacting geopolymer concrete
SD	Slope deflection matrix
SMRF	Special moment resisting frames
SNI	Indonesian standard specifications
SP	Superplasticizer
UPV	Ultrasonic pulse velocimeter
WGC	Workable geopolymer concrete
x	Distance x from the beam-column joint (mm)
α_h	Haunch angle (degree)
Δ	Deflection (mm)
θ	Joint rotation (radians)
τ	Shear strength (MPa)

I. Introduction

Earthquake provisions in South East Asia were modified as a consequence of the alteration in earthquake zone mapping. Therefore, buildings that were designed and constructed prior to the introduction of these new codes no longer meet the load carrying capacity requirements. For these moment resisting frames (SMRF), the underlining design principle is the philosophy of a strong column and a weak beam. Energy dissipation is designed to occur within the beam elements, since the formation of plastic hinges in the beams (rather than in the columns) results in better ductile behavior in the frame [1], [2]. The formation of plastic hinges is located adjacent to the column face, where the shear and flexure stresses are at a maximum. The development of plastic hinges and decrease in steel diameter, as a consequence of Poisson's ratio, leads to loss of bonding in the reinforcing steel and concrete. Joint rigidity then further declines, accelerating the failure process in the overall frame.

The requirements of most standards allocate close-

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spaced stirrups to ensure that this critical section will not fail in shear. For the design of this beam-to-column area, the stresses in the flexural-tensile reinforcement might be taken as 1.25 times the yielding stress of the longitudinal reinforcement. Additional guidelines for SMRF are that the column dimensions in the direction of the beam's longitudinal reinforcement, are at least twenty times this longitudinal reinforcement diameter (Fig. 1). The new earthquake provisions resulted in a demand for higher load carrying capacity and more ductile behavior of the SMRF. These requirements need to be resolved (with methods other than demolition and rebuilding) to ensure the sustainability of older concrete structures [3].

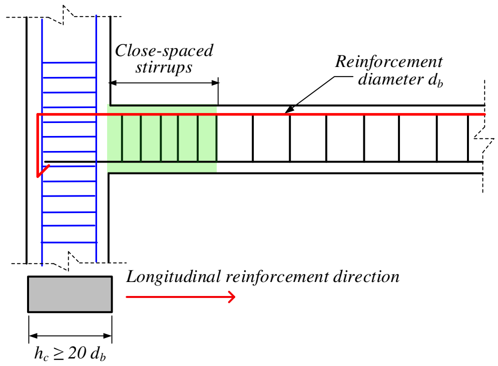


Fig. 1. Code provision for cyclic joint design

This work proposes a combination of methods and means to improve the capacity of an SMRF by using a haunch for the exterior, as well as interior joints, in combination with the application of self-compacting-geopolymer-concrete (SCGC). The fundamental idea was to combine a structural solution with an environmentally friendly concept, as it is well known that geopolymer concrete has a zero-cement consumption [4]. Furthermore, geopolymer concrete uses fly ash, which is a waste by-product of the coal industry. The haunch shifts the location of a plastic hinge away from the beam-column joint's face while, on the other hand, reduces the effective length of the beam (Fig. 2). The reduction of this effective length has positive impacts on both the service load carrying capacity and the deflection of the member, while the shifting of the hinge formation postpones plasticization.

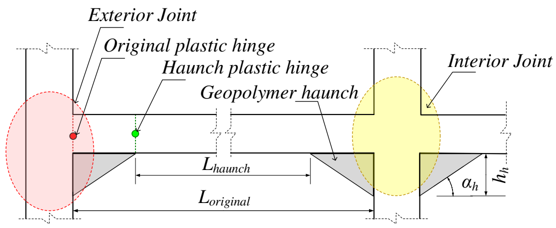


Fig. 2. Illustration of the geopolymer haunch

In Fig. 2, α_h is the haunch angle, h_h is the haunch depth and $L_{original}$ and L_{haunch} are the prismatic and haunch section's corresponding clear spans.

The paper evaluates the state-of-the-art on the most recent haunch developments as a flexural member's retrofitting method. The study of the material used for the haunches and the outcome of research-work conducted nationwide, is summarized. A chapter focusing on the geopolymer mechanical and physical material properties used for the haunch is presented. The specific characteristics of the self-compacting-geopolymer-concrete (SCGC) as compared to ordinary concrete mixes are explained, and the method of obtaining a flowable concrete required during casting is elaborated. A case study on a field application of a geopolymer haunch is presented. The study is unique since the water-loading technique is accessed. The load-deformation responses due to the increment loading sequence was recorded and analysed at mid-span and at the haunch-tip. A numerical simulation of a prismatic member was developed to compare the influence of the haunch on the structure. The summary of results and conclusions are presented at the end.

II. State of the Art on Haunch Elements

References [5]–[8] all concluded that haunch elements are more effective than prismatic members. Furthermore, their research results, based on cyclic experiments performed on haunch and prismatic beams (with and without shear reinforcement), stated that the factors influencing the effectiveness of the haunch were: the haunch angle, the concrete compression strength ratio to the original element, the presence of shear reinforcement and the presence of inclined longitudinal reinforcement. The specimens in [5], [6] were simply supported and subjected to a two-point loading system. [7], [8] executed tests on actual interior beam-column joints. The haunch resulted in gradual crack formation along the haunch-length, as a result of the arch mechanism. The failure mode became less friable compared to the abrupt failure of the prismatic members. The research underlined that the load carrying capacity, stiffness and energy dissipation were positively modified by the haunch. The stiffness and the dissipating hysteric energy increases, as a function of the increase in haunch-angle from the horizontal line. Additionally, [6] found that tensile reinforcement rebars had a negligible contribution to the shear performance of the joint. The study of [9] focused on interior joints with no stirrups and concluded that these beams could exhibit fatigue; the fatigue mode could be distinguished into shear and reinforcement fatigue. The shear fatigue was a function of the haunch depth, while reinforcement fatigue was influenced by the slenderness of the element at mid-point. Reference [10] studied the numerical comparison of SMRF responses between haunch and prismatic members and concluded that the characteristics of haunch connections influenced the lateral deflection, base shear, frame stiffness and natural period.

To date, the majority of the research on reinforced concrete haunch elements is focused on the principles of a monolithic haunch. These structures are designed as a haunch element and produced simultaneously with the beam and column. The retrofitting of existing members using concrete for performance enhancement has scarcely been investigated. The existing methods include: the use of steel haunches as post-installed haunch anchors [11] and the double-diagonal-axial steel haunch assembly anchored to the joint [12]–[15]. Variations in fiber reinforced polymers (FRP) joint reinforcement and haunch connection were investigated by [16]. Reference [17] evaluated the effectiveness of double and single steel haunch systems. Most recently, joint retrofitting combined with jacketing and haunch elements was studied by [18] and the application of buckling, restrained haunches was conducted by [3], while [19] studied exterior joints using diagonal haunches.

All of the above-mentioned systems were constructed using steel elements. Steel elements have the disadvantage that routine maintenance is required to prevent deterioration due to rust, or the disintegration of connecting elements such as the bolts and anchorages. The application of concrete haunches is scarcely used. Reference [20] attempted to revitalize damaged beam-column joints with a wire-mesh-in-concrete jacketing and showed that the repaired joint was retrieved to its original state. The research of [21], [22] focused on the application of concrete haunches in SMRFs. The work investigated the single and double concrete haunch of a two-story SMRF. The haunches were constructed using conventional concrete. The study of [23] shed a light on the comprehensive experimental study of concrete haunch beams and concluded that the failure mode is greatly influenced by the presence of shear reinforcements, the stiffness decreased as the haunch inclination angle increased and the first crack was characterized by pure flexure at mid-span.

The concept of using a concrete haunch in combination with the utilization of geopolymer concrete is explained in this work. A concrete haunch needs to be carefully designed. Issues such as interface bond performance between the member and the haunch, differentiation in the long-term effects between the geopolymer and conventional concrete, and the manufacturing process' technical detailing have to be considered. A crucial aspect is the workability of geopolymer mixes that tend to be stickier and therefore less flowable. A disadvantage of a geopolymer-based haunch is the prolonged curing time; geopolymer concrete is known to have a much longer curing time compared to conventional concrete [4], [24], [25]. The design approach, including mix-design theories, is not well established. Most recent research on these aspects can be found in the work of [26], [27].

III. Geopolymer Response as a Composite Material

Geopolymer concrete has gained popularity in recent years. The state-of-the-art can be found in the researches carried out by [4], [24]–[26]. Reference [28] compared the behavior of geopolymer concrete to conventional concrete. The geopolymer concrete utilized for the haunch in this study used a *type F* fly ash (Fig. 3) in combination with a sodium hydroxide (NaOH) and sodium metasilicate (Na_2SiO_3) Be-52 activator. The (Na_2SiO_3) Be-52 has a less concentrated solution, compared to (Na_2SiO_3); (Na_2SiO_3) dissolves in water.

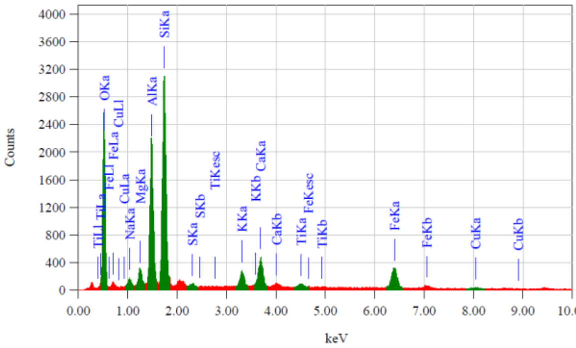


Fig. 3. EDX analysis of type F fly ash

One of the major challenges in using this concrete for the haunch is its low workability, in combination with the highly adhesive nature of the mix. Research has shown that the addition of superplasticizers, in combination with a proper mix design, could overcome this problem. In contrast to ordinary concrete, geopolymer concrete's binding strength is a consequence of a reaction between fly ash and activators [25], [29], [30]. The fly ash's chemical reaction is activated by NaOH (with a molarity of 8 to 14) and Na_2SiO_3 [31]. Reference [32] concluded that a 12 molar solution yielded an optimum strength. The ratio between these two activator components ranges from 0.4 to 2.5 [33]. Furthermore, the geopolymer concrete is categorized as an environmentally friendly, 'green' concrete because of its potential to reduce the production of CO_2 to 20% [29], [34]. Theories regarding the design mix proportions of geopolymer concrete have not been well established in great detail until now. One of the major challenges is the fluctuation in the chemical profile of the fly ash, which is highly dependent on the origin of the coal. The results of the research conducted to define a mix proportion for the fly ash chemical profile are presented in Fig. 3; a highly flowable mix (i.e. SCGC) is described. Aggregates with a maximum size of 10 mm were used and to enhance the flowability, superplasticizers, low volume Portland cement and extra water were added. The water had a most prominent influence on the workability but it can negatively affect the strength.

III.1. Mix Design of SCGC

Limited research is available on the mix design of geopolymers. Two trial mixes were produced to explicate the impact of activators and superplasticizers, resulting in the *Workable Geopolymer Concrete* mixes WGC-1 and

WGC-2 [35]. These trials were based on the EFNARC standards that mandated a slump flow measured by the Abrams-Harder cone of 650-800 mm. Studies by [25] suggest an extra water-to-fly-ash ratio of 0.3. To further improve the workability of the fresh concrete, a superplasticizer was used. The WGC-1 activator comprised 12 molar NaOH in combination with Na_2SiO_3 Be-52. The mix used an aqueous solution of modified polycarboxylate copolymers with a total chloride ion content below 0.1% w/w, denoted as SP-1. The WGC-2 activator was a 12 molar NaOH and Na_2SiO_3 combination with a carboxylic ether polymer (with long side-chains), denoted as SP-2. This new generation superplasticizer improved the cement dispersion effectiveness due to the side-chains being linked to the polymer backbone, generating steric hindrance that stabilized the cement particle separation and dispersion process. WGC-1 resulted in a slump flow of 300 mm, while WGC-2 had a slightly improved flow of 325 mm. Since the polypropylene homopolymer from the Be-52 had a positive impact on the workability, the use of Na_2SiO_3 Be-52 and SP-2 were combined, resulting in an SCGC with a 650 mm flow. The final mix design of basic SCGC materials is shown in Fig. 4. Table 1 presents a detailed outline of the trial mixes WGC-1, WGC-2 and the SCGC. FA stands for fly ash, AA for alkaline activator and SP for superplasticizer.

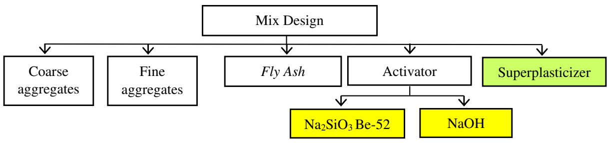


Fig. 4. Mix proportion of SCGC haunch [35]

TABLE I
WGC AND SCGC MIX PROPORTIONS

Material proportion % w/w	WGC-1	WGC-2	**SCGC**
Aggregates-to-[FA+AA] ratio	7.0 : 3.0	7.0 : 3.0	**7.0: 3.0**
Fine-to-coarse aggregate ratio	4.0 : 6.0	4.0 : 6.0	**4.0 : 6.0**
FA-to-AA ratio	6.5 : 3.5	6.5 : 3.5	**6.5 : 3.5**
NaOH-to-Na_2SiO_3 ratio		1.0 : 2.5	
NaOH-to-Na_2SiO_3 Be-52 ratio	1.0 : 2.5		**1.0 : 2.5**
Superplasticizer [SP-1]	2.0		
Superplasticizer [SP-2]		5.0	**2.0**
Extra water	11.7	12.0	**11.7**
Portland cement	5.6	6.6	**5.6**
Concrete compression strength (MPa)	31.2	28.3	**32.5**
Slump flow (mm)	300	325	**650**

The properties of geopolymer and conventional concrete were evaluated in correlation to their function as strengthening materials. The geopolymer concrete strength was determined based on the cylindrical specimens prepared at the time of haunch fabrication, and tested at the age of 28 days. Table 2 represent the SCGC properties as compared to conventional concrete having an identical strength.

While the compression and shear strength were almost identical, two testing methods addressed to divine the tensile strength showed that the SCGC presented a much better tensile performance with an increase of 50% compared to conventional concrete. The steel-to-concrete SCGC bond improved by 63% due to the chemical bond of the geopolymer concrete. The workability of the SCGC was measured to be 650 mm, compared to the 80 mm slump of the conventional concrete. The highly flowable mix promoted a compact and homogeneous haunch, with optimum bond between the conventional and geopolymer concrete. It was concluded that a good compatibility performance between the frame and the haunch would be maintained throughout the loading's sequence. The use of geopolymer concrete as haunch closely resembles the behavior of a conventional concrete haunch with the same strength, but providing the advantage of a greener concrete, a better steel-to-concrete bond and a higher tensile strength.

TABLE 2
SCGC AND CONVENTIONAL CONCRETE MECHANICAL PROPERTIES

Remarks	Conventional Concrete	SCGC	Code
Cylinder compressions strength 28 days f'_c (MPa)	32.62	32.52	SNI 1974-2011 ASTM C39M
Split cylinder tensile strength f_{tr} (MPa)	1.59	2.38	ASTM C307
Flexure tensile strength f_{MR} (MPa)	2.76	4.56	SNI 03-4154-2014
Steel-to-concrete bond (MPa)	0.99	1.62	ASTM C1583
Shear strength τ (MPa)	0.52	0.54	ACI 318
Slump (mm)	80	650	AASHTO-2014 EFNARC-Standard 2005
Slump flow time (seconds)	-	3.28	ASTM C11611M European Guidelines 2005 (T50)

IV. Case Study on Geopolymer Haunch Members

Preliminary research was conducted on an existing building that was designed in accordance with previous codes. After a moderate quake in the area, it was visually observed that cracks were present in the beams and slab.

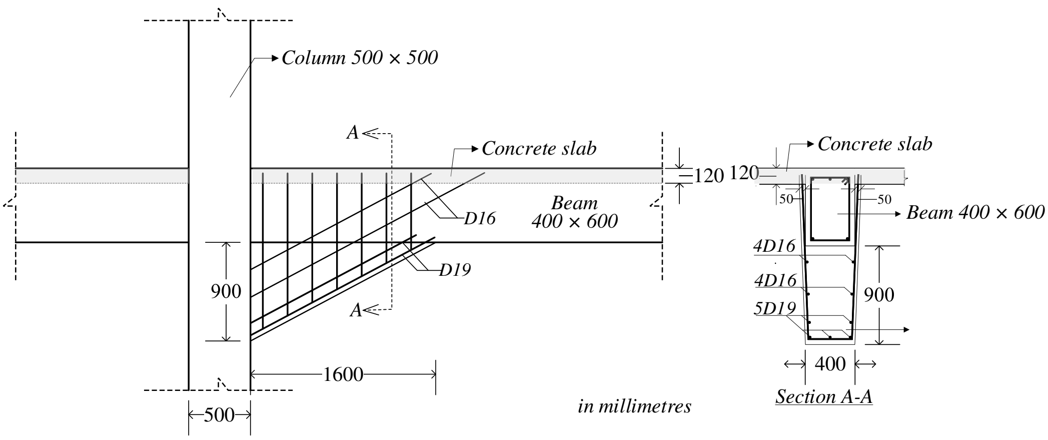


Fig. 5. SCC haunch detailing

Furthermore, the beams exhibited noticeable deflections and severe vibration was felt under service loading. First, an assessment of the building's condition was performed to evaluate whether the structure could be conserved and, if so, what techniques should be implemented to rehabilitate and upgrade the SMRF to meet the current code. For this investigation, core samples were taken to obtain the concrete's compressive strength. The cylindrical strength of the concrete was determined from cored drilled specimens, taken from the field resulting in a strength of 14 MPa for the columns, and 19 MPa for the beams. Using an Ultrasonic Pulse Velocimeter (UPV) and a rebar locator, the density and the properties of the sections were reconstructed. Based on the gathered data, a three-dimensional structural analysis was conducted, considering long-term effects, such as concrete carbonation, shrinkage and creep.

The structure was a one-span building with no interior joints. The beam had a clear span of 6700 mm and section a dimension of 400 × 600 mm, including the 100 mm thick slab and 20 mm floor coating. A rehabilitation plan was chosen, including crack grouting with a high-grade epoxy resin and retrofitting using a geopolymer concrete haunch. Prior to grouting and retrofitting, the beam was straightened into its original position. It was calculated that a geopolymer haunch with a height h_h of 900 mm, a haunch-angle α_h of 29.3^0 and a 28 days compression strength of minimum 30 MPa would be sufficient to repair and rehabilitate the structure (Fig. 5). Previous research indicated that a larger angle would be more effective. However, this would hinder the free space profile within the room due to the limited structural frame height of 3800 mm. To validate the outcome, a full-scale test was conducted on the structure after the rehabilitations have been applied. The test was executed by the water-loading system, since this method guaranteed a uniform loading and a controlled increase and decrease-rate (Fig. 6). The test set-up is shown in Fig. 7. A water basin was placed on the slab and the loading on the beam was controlled through the water depth accumulating in the basin. The basin was emptied during un-loading and the increment rate was carefully monitored. The water-loading technique is a unique method for ensuring a uniform, controlled loading sequence. Additionally, this method is inexpensive and requires less advanced equipment.

Three steel cables, with a 2 mm diameter, were utilized to measure the vertical deflection at mid-point and at the tip of the haunches (1600 mm from the column face). The cables were connected with the Linear Variable Differential Transformers (LVDT) through a pulley-system, equipped with a weight as can be seen in Fig. 7. The vertical movement of the weight was measured by the LVDTs to represent the vertical deflection of the beam at the specified locations.

(a)

(b)

Fig. 6. Uniform loading system by submerging (a) water-loading method (b) load control through water depth measurement

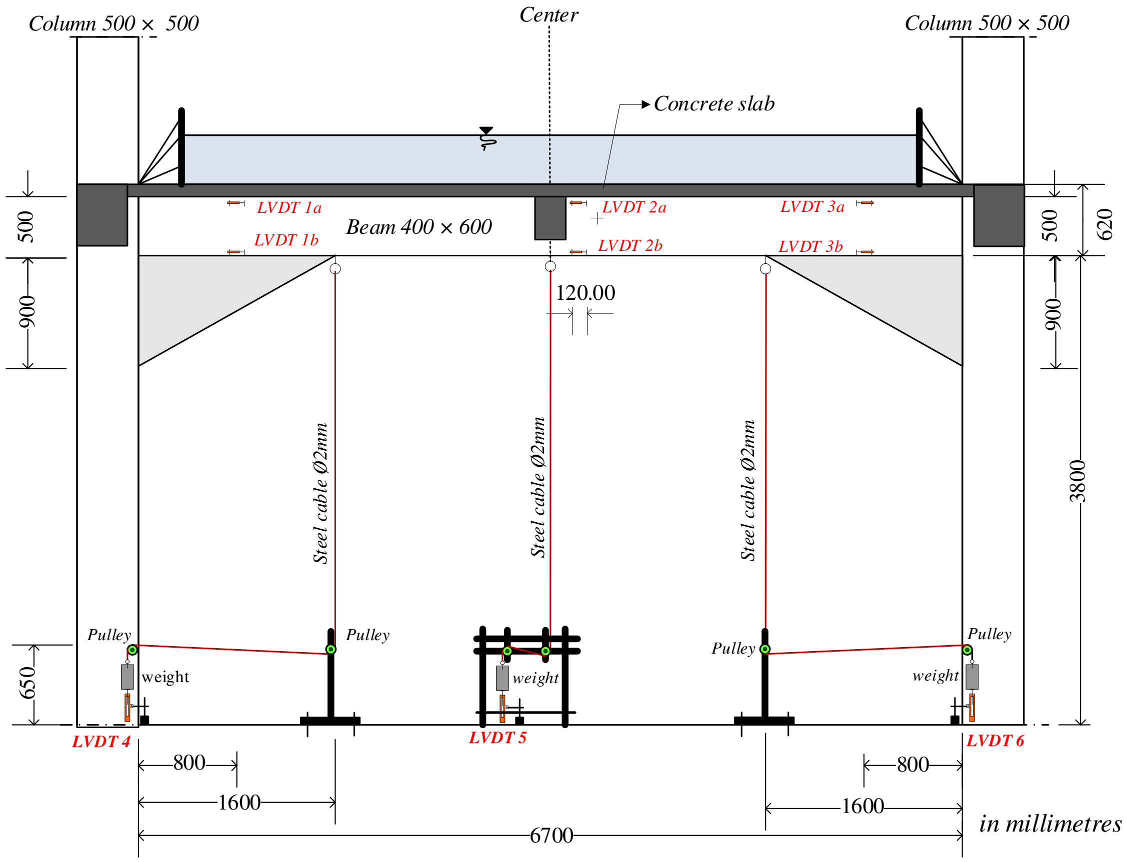
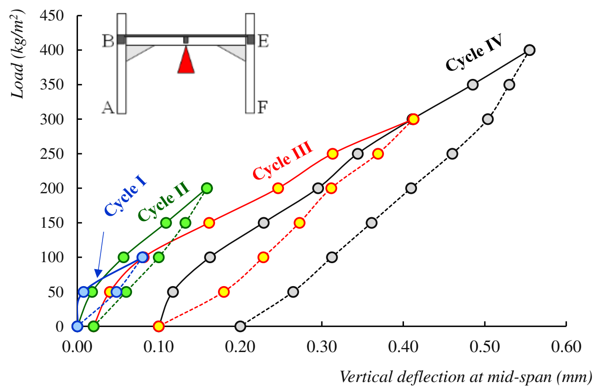
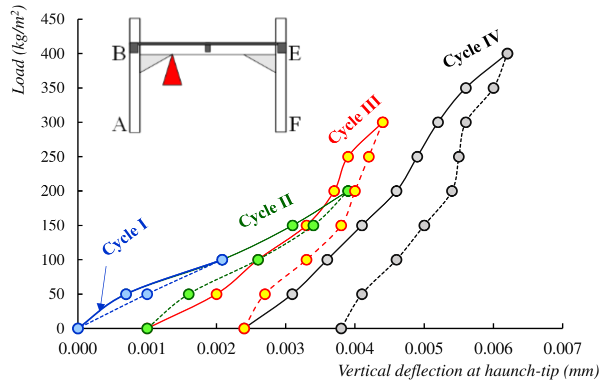


Fig. 7. Loading test of the actual frame

The test was aimed at monitoring the response of the revitalized structure by applying four loading cycles with a magnitude of 100 kg/m^2, 200 kg/m^2, 300 kg/m^2 and 400 kg/m^2, respectively. The incremental load was applied with an augmentation of 50 kg/m^2. The digital data were synchronized and the load versus deflection response was recorded, as shown in Figs. 8(a) and 8(b). The deflection response of the beam at the location of the two haunch-tips was identical and the averages of the two readings were taken to illustrate their deflection responses.



(a)



(b)

Fig. 8. Load-deflection response on (a) mid-span (b) haunch tip (1600 mm from column face)

Fig. 8a shows the load-deflection at the mid-span. During the first cycle the member behaved in an elastic manner, a deflection of 0.08 mm was recorded with no residual deflection upon load removal. The stiffness of the member decreased during the ascending branch of the curve but increased on the descending part of the loading path, as was expected. This pattern was followed by all of the other cycles but the divergence in the residual vertical deflection became more pronounced at the end of every cycle. After the second cycle, a permanent deflection of 0.02 mm was detected. The permanent

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deflection accumulated until a permanent deflection of 0.20 mm remained in the structure after the last cycle.

Fig. 8b presents the load-deflection at the tip of the haunch. The overall response is far less intense when compared to response at mid-span. A permanent deflection of 0.004 mm resulted, demonstrating that the haunch provided a very high rigidity at the beam-column-joint. The deflection response at the haunch-tip was significantly lower, underlining the importance of the haunch in providing a higher member stiffness and re-locating the potential plastic hinge formation. The residual deflection was only 19% of the residual deflection at the mid-point.

It is interesting to evaluate the effect of the haunch on the deflection behavior as a response to the load. Table 3 represents the maximum deflection of the retrofitted member as compared to the theoretical deflections of a prismatic member subjected to identical loading. Figs. 9(a) and 9(b) represent the deflection at mid-span and at the haunch-tip, 1600 mm from the column face with respect to the load. These graphs express the degree to which the maximum deflection progresses when the load is increased.

TABLE 3
MAXIMUM PRISMATIC VERSUS HAUNCH DEFLECTION

Load (kg/m^2)	Mid-Span Deflection (mm)		Haunch-Tip Deflection (mm)	
	Haunch member	Theoretical Prismatic	Haunch member	Theoretical Prismatic
0	0.08	1.49	0.002	0.836
100	0.16	1.80	0.004	1.015
300	0.41	2.11	0.004	1.193
400	0.55	2.42	0.006	1.373

The theoretical deflection calculation for the prismatic section was conducted by constructing the slope deflection matrix [SD] based on the fixed end moments (Table 4). The fixed end matrix [M_{FEM}] was calculated from the water-loading q. The [SD_{all}] matrix for the overall structure was generated.

TABLE 4
SLOPE DEFLECTION MATRIX [SD]

Joint	Joint rotation × EI/L				M_{FEM}
	θ_B	θ_C	θ_D	θ_E	
B	33.4×10^{10}	5.7×10^{10}	0	5.3×10^{10}	-6.1×10^7
C	5.7×10^{10}	22.0×10^{10}	5.3×10^{10}	0	-6.1×10^7
D	0	5.3×10^{10}	22.0×10^{10}	5.7×10^{10}	6.1×10^7
E	5.3×10^{10}	0	5.7×10^{10}	33.4×10^{10}	6.1×10^7

Where θ is the joint rotation, and EI/L the stiffness of the member. Joint B and E are designated for the first story joints, and C and D for the second level joints. From the multiplication of the inverse slope deflection matrix $[SD]^{-1}$ and the fixed end moment matrix [M_{FEM}], the rotation at each joint was acquired (Table 5).

TABLE 5
JOINT ROTATION MATRIX [θ_i]

Joint	Rotation θ_i (radians)
A	0
B	1.53251×10^{-4}
C	3.12207×10^{-4}
D	-3.12207×10^{-4}
E	-1.53251×10^{-4}
F	0

The actual joint moment was a result of the matrix operation between the structural slope deflection matrix [SD_{all}] and the joint rotation matrix [θ_i] as expressed in (1).

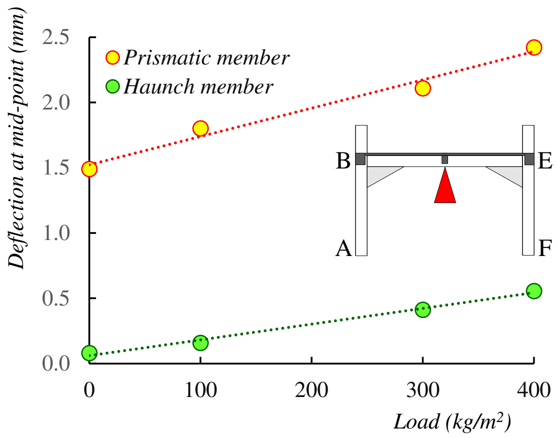
$$\left[M_{ij}\right] = \left[SD_{all}\right]\left[\theta_i\right] \tag{1}$$

The deflection equation was calculated through double integration of the generalized moment equation (2). The deflection was derived from (3).

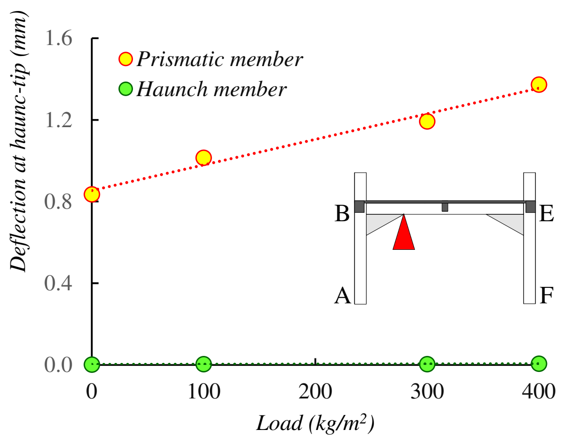
$$M_i = \frac{1}{4}qLx - \frac{1}{4}qx^2 + M_{ij} \tag{2}$$

$$\Delta = \frac{\frac{1}{12}qx^3 - \frac{1}{24}qx^4 - \frac{1}{24}qL^3x + \frac{1}{2}M_{ij}Lx - \frac{1}{2}M_{ij}x}{EI} \tag{3}$$

Nonlinear behavior of the concrete material was incorporated in the calculation based on the stress-strain relationship as outlined in the *fib* 2010 code. The adjusted stress and strain due to the deflection was used to determine the secant modulus of elasticity E_{sec}. An iteration process was conducted to re-calculate the modified deflection based on the adjusted modulus of elasticity, and this cycle was repeated until a state of convergence was reached, giving the theoretical prismatic deflections as presented in Table 3.



(a)



(b)

Fig. 9. Deflection versus load degree on (a) mid-point (b) haunch-tip

The analyses show that the haunch member has a substantially higher stiffness depreciation rate when compared to the prismatic member. The mid-point and haunch-tip section of the retrofitted member had a relative deflection-to-load ratio of 0.002, compared to the 0.001 ratio calculated for the prismatic member. The stiffness depreciation ratio was determined based on the first derivative of the normalized deflection versus load function, and reflects the tangent of the curves.

V. Retrospective View and Conclusions

Previously designed and constructed moment resisting frames (SMRF) might require service, as well as ultimate load carrying capacity enhancement due to a range of diversities including code alterations, aging or function re-assignment. To conserve buildings and minimize the need for demolition, a method was developed to revitalize a flexural member while contributing to the environment by using a cement-less concrete. The designed approach utilized a combination of a concrete haunch and a self-compacting-geopolymer-concrete (SCGC). The aim of the haunch was to re-locate the formation of the plastic hinges, increasing the member's stiffness at the beam-to-column area and improving the beam's service load carrying capacity. The method for designing the mix to create a flowable geopolymer that could permeate the haunch was outlined and the basic material properties used for this mix were explained. The resulting SCGC had a horizontal flow of 650 mm, this was sufficiently liquid to produce a dense and homogeneous haunch.

The method was tested at full-scale on an existing building that had visible cracking due to overloading. Before placing the haunches, the beam was straightened and injected with an epoxy resin. Two exterior haunches were constructed at the beam-to-column joint; the SCGC had a 28 days cylindrical compression strength of 32.5 MPa. The frame was further tested with incremental loading up to a maximum of 400 kg/m^2. The deflection at maximum loading for each cycle was carefully recorded, as was the residual deflection at the end of the loading stage.

The test results show that the geopolymer haunch performed well in accommodating the load (no cracks were detected) and the member's initial stiffness at every loading stage was within the elastic limits. The service load carrying capacity of the structure was significantly improved, as was the corresponding deflection. The measured deflection at the mid-span was only 23% of the predicted deflection of the prismatic section. The haunch was also effective in re-locating the potential plastic hinge: the vertical deflection at the haunch-tip only measured 0.006 mm at a maximum loading of 400 kg/m^2.

Since the member was subjected to a negative bending moment at the beam-to-column joint, this experiment could not conclusively prove whether the bond between the geopolymer and conventional concrete will be a challenge. Furthermore, a double haunch is advised when the building is subjected to extensive sign-reversed moments, since a haunch on the bottom part of the beam-to-column joint is only effective for a negative bending moment.

An interesting finding was that the rate of stiffness decrease reflected in the deflection-to-load ratio was higher for the retrofitted member, when compared to the prismatic one. The rationalization of this outcome is as follows. First of all, the haunch structure has a non-uniform section with a non-uniform modulus of elasticity due to the use of a combination of geopolymer and conventional concrete. The behavior of such a complex, multi-variable member differs from prismatic, uniform sections. Secondly, the effect of straightening created converse-signed strains in both the concrete and the reinforcing steel; the tensile steel was pre-compressed as a result. This pre-straining alters the behavior of the tensile steel under loading. Thirdly, the tensile steel yielded and the tensile strength therefore diverged from that of the original material. Finally, the epoxy retrofitting created patches with significantly different material properties, compared to the concrete. Taken altogether, these factors contributed to faster stiffness depreciation under incremental loading. To identify each influence, a finite element model should be constructed to study the behavior of each variable separately.

The haunch SCGC retrofitting technique provides an efficient and environmentally friendly method of frame revitalization and can be used to prolong the lifetime of buildings.

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