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Flexural Performance of I-Joist Fabricated with Glue-Laminated Bamboo and *Gmelina arborea* Plywood

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Abstract

The search for efficient and versatile structural elements, leads to the fabrication of I-joists (6.5 cm × 18.5 cm × 600 cm (width × depth × length) with glue-laminated bamboo (*Guada angustifolia*) in the flanges and *Gmelina arborea* 12-mm structural plywood in the web. The results showed a modulus of rupture (MOR) of 39.45 MPa and an effective modulus of elasticity (MOE) of 17.05 GPa. Shearing in the glue line was 5.95 MPa and the lamination strength was 6.45 MPa. Structural design values averaged 9.43 MPa for bending and 4.72 MPa in shear according to Costa Rican structural standards. Both resistance value (flexure and shear) were considered satisfactory for structural proposes and I-joists fabricated with bamboo and *G. arborea* plywood are comparable with the Andean classification group "C" structural grade. The use of this I-joist was also shown in roofing and flooring systems. This beam can be used in allowable spans from 2 to 4 m in span for flooring systems and from 5 to 7 m for roofing applications.

Keywords

***Guadua angustifolia*, Flexural Strength, Shear Strength, Plantation Wood, Tropical Material**

1. Introduction

Bamboo is an alternative material of great worldwide potential, due to its great diversity and availability [1]. It is estimated that there are about 1250 species, however only 20 of them have been studied and are considered suitable for structural applications [1]. Bamboo has been used in construction for centuries, due to its excellent

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strength in relation to this weight, high sustainability, growth rate (usually less than 5 years) and its flexibility allowing the creation of different geometric shapes [2]. However, there is little research on the manufacture of laminated bamboo [2], despite the high structural strength available [3].

Costa Rica, as a small country with limited area, generates a series of raw materials for the production of laminated beams. Plantation timber such as *Gmelina arborea*, *Tectonagrandis* and *Acacia mangium* [4] and bamboo of *Guadua angustifolia* [5] stand out because of their availability and appropriate characteristics.

Guadua angustifolia Kunt. (Poaceae) species is notable for the large size of its culms, which reach up to 25 meters and 10 to 18 cm in diameters [1]. These culms have been used in the construction of homes, hotels and bridges. Studies conducted by Aschheim *et al*. [3], Nugroho and Ando [6], López and Correal [1], Xiao *et al*. [7] and Wei *et al*. [2] have shown the structural nature of this material. Nugroho and Ando [6] developed a composite beam, wood reinforced with bamboo, while López and Correal [2] and Wei *et al*. [2] constructed structural laminate manufactured bamboo beams with *G. angustifolia* and *G. Phyllostachys*. Xiao *et al*. [7] constructed hybrid "Glubam" beams made of wood/bamboo. Recently Aschheim *et al*. [3] produced I-joists, with bamboo flanges and oriented strand board (OSB) or plywood in the web.

Although, different sections can be used to achieve efficient I-joist and flexural strength, the structural behavior is governed by the cross section [8]. An efficient I-joist is one in which the material is located as far from the neutral axis as possible, increasing the section modulus, resulting in a greater bending moment [8]. Another desirable feature of an efficient I-joist is flange greater width in order to achieve greater lateral stability [8].

The growing requirement to develop composite materials based on wood, such as plywood, laminated beams, I-beams, etc. [9]-[11] causes the development of composite products from wood and bamboo plantations, to become an option in countries which lack extensive plantation sites but have bamboo plantations suitable for building purposes [12]. The manufacture of a composite bamboo and plywood I-joist, becomes a feasible option, with plywood structural features web [4] [13] and glulam bamboo flanges, using larger lamellas made from curved sections obtained from the longitudinal cutting of the bamboo culm.

Finally, the search for versatile and efficient, primary structural elements for construction, generated particular interest in the I-joist considered in this study which is fabricated with bamboo laminated in the flanges and structural plywood in the web. The objective of this study is to determine design values for resistance and develop design tables for the application of the I-joist in floor and roof systems.

2. Material and Methods

2.1. Materials

The I-joist samples have two components: i) flanges manufactured with glue-laminated bamboo (*Guadua angustifolia*); and ii) the webs made of *Gmelina arborea* structural plywood. The bamboo used in this study comes from "Arenal" located in the province of Guanacaste, Costa Rica. The bamboo plants were 4 years old, having an average diameter of 10 cm and length of 4 m. The plywood was made from *G. arborea*'s wood from plantations of fast growing trees harvested from between the 3rd (at 9 years old) and the final harvest (at 12 years-old) in the southern region of Costa Rica [13].

2.2. I Joist Design

The I joists were constructed with laminated bamboo flanges (**Figure 1(a)**) and a web made of 12 mm thick G. arborea plywood (**Figure 1(b)**). The lamellae's greatest possible dimension is used in the flanges allowing manufacturing the flange as long as it allows. Five pieces of 12 mm thick plywood were required for each web. This plywood is the most commonly available in Costa Rica's market and meets the structural requirements needed [13]. The resulting I-joist dimensions are 6.5 cm wide and 18.5 cm deep (**Figure 1(c)**). The flanges were designed with an average of 15 lamellae sheets, each one approximately 4 mm thick. In the flange, the lamellas were glued tangentially along their length parallel to the axis of the beams resulting in vertically oriented gluelines (**Figure 1(c)**).

2.3. Manufacture Process

The flanges were built at the Xilo SA Company (www.grupoxilo.com) and in the Forest Industry Integration

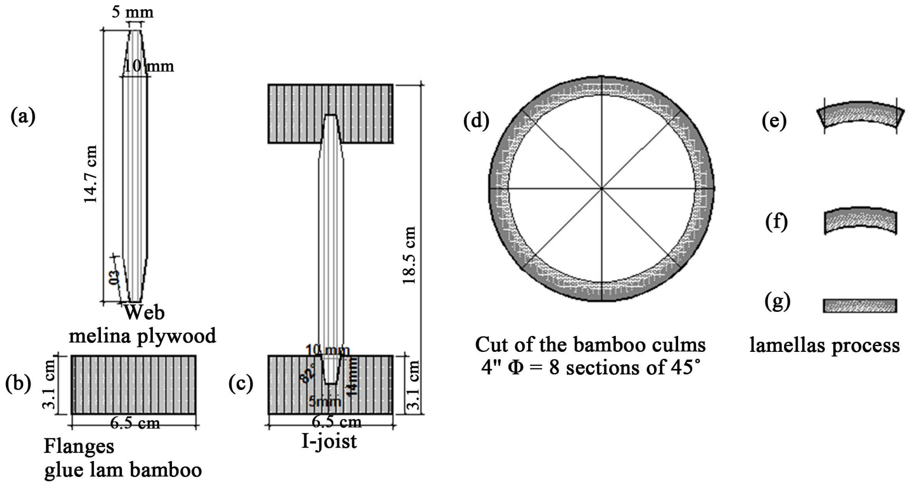

Figure 1. I joists design (a), (b) and (c), lamellas obtained from the culms (c) to (g).

Center from the Technological Institute of Costa Rica. The bamboo culms were cut, using the sectioning process into 8 sections of approximately 45 degrees each (**Figure 1(d)**). The strips (bamboo lamellae) were dried to 12% moisture content in a solar kiln [14]. Dried-strips were cut to 3.5 cm in width (**Figure 1(e)** and **Figure 1(f)**). Afterwards both faces of the strips were planned to their final thickness of approximately 4 mm (**Figure 1(g)**). 15 or 16 strips were glued to shape a laminated flange (**Figure 1(b)**). For gluing strips, melamine urea formaldehyde was used at a pressure of 1.07 MPa for 8 hours at room temperature of 22˚C and 65% in relative humidity. Finally, this flange was planned and obtained this final dimension of 3.1 by 6.5 cm. Finally, a channel was cut into which the plywood web was connected (**Figure 1(c)**).

2.4. Mechanical Tests

The I-joists were tested in third-point static bending over a span of 3.36 m as shown in **Figure 2**. Testing was conducted with a Tinus Olsen universal testing machine, with 60 ton capacity. The test conditions, load speed and deflection determination were compliant with ASTM D198-09 [15]. From the results of these tests, the modulus of elasticity (MOE) and modulus of rupture (MOR) of the I-joist are found using Equations (1) and (2), respectively.

$$MOE\left(\text{GPa}\right)=\frac{0.852\cdot F_{LP}\cdot L^3}{24\cdot I\cdot y}\times 0.0000981 \quad (1)$$

$$MOR\left(\text{MPa}\right)=\frac{F_{\max}\cdot L\cdot \frac{H}{2}}{6\cdot I}\times 0.0981 \quad (2)$$

where: F_{LP} = load at proportional limit (kg), $F_{\max}$ = rupture load (kgf), L = span (cm), I = moment of inertia (cm^4) for I form, y = deflection (cm) and H = depth of the I-beam (cm), 0.0000981 conversion units from $kgf\cdot cm^{-2}$ to GPa and 0.0981 = conversion units from $kgf\cdot cm^{-2}$ to MPa. And 0.852 is derived from general equation for MOE for two load (Equation (3)) [15], where a = $L/3$

$$E=\frac{P\cdot a\left(3L^2-4a^2\right)}{24\cdot I\cdot y}=\frac{P\cdot\left(L/3\right)\cdot\left[3L^2-4\left(L/3\right)^2\right]}{24\cdot I\cdot y}=\frac{\frac{P\cdot L}{27}\left(27L^2-4L^2\right)}{24\cdot I\cdot y}=\frac{0.852\cdot F_{LP}\cdot L^3}{24\cdot I\cdot y}\times 0.0000981 \quad (3)$$

2.5. Density Determination, Beams Weight and Glue Line Test

Following bending tests, a 5-cm cross-section was extracted from the I-beam and weighed. Its volume was determined to calculate the density ($kg\cdot m^{-3}$). This value was later used to calculate total weight of the I-beam. For glue line test, on the same I-joist that was tested, another sample of approximately 25 cm length was taken from

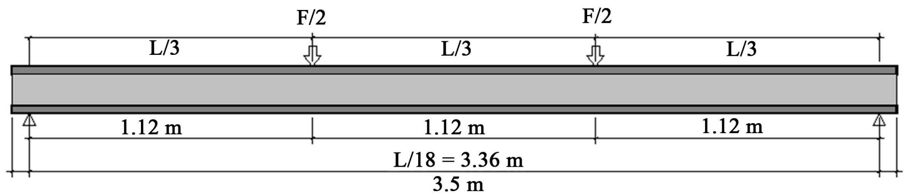

Figure 2. Loading arrangement for the flexure test.

the flanges, from a section away from the failure area. From this, samples of 6.5 cm in length were extracted (60 samples in total) and tested according to ASTM D905 [16]. All the samples were separated into two groups of 30; on one group, shear testing was performed on the adhesive line and on the other group, the fiber shearing between two glue lines was tested.

2.6. Derivation of Design Properties

Design values were derived from MOE and MOR values of I-joist tested in flexure test and its applicability will be shown as floor and roof systems. In the derivation of design values, the beam was structurally analyzed in 3 different ways: i) bending capacity, ii) shear capacity and iii) deflection in the span. For bending capacity, the maximum load that a 6 m length of I-beam with various depths could withstand was determined, taking into account only maximum stress of the transverse section. To determine shear capacity, maximum shear values in supports produced by the maximum load distributed over the length of I-beam was ascertained. Finally, maximum deflection produced by maximum load distributed over the length of I-beam was determined. To derive design properties, Equations (3)-(5) were used [17]:

$$Mpp(\text{Kg-m}) = \frac{\text{Weight} \cdot L}{800} \tag{4}$$

$$Mrup(\text{Kg-m}) = \frac{F_{\max}}{200} \cdot \frac{L}{300} + Mpp \tag{5}$$

$$MORc(\text{MPa}) = \frac{Mrup \cdot (H/2)}{I} \times 0.0981 \tag{6}$$

where *Mpp* = weight moment due to beam dead load, *Mrup* = moment of rupture in flexure, *MORc* = modulus of rupture in shear and 0.0981 = conversion units from kgf·cm^{-2} to MPa.

Using MORc values, a frequency distribution was carried out. The lowest fifth percentile was selected as the bending value used for bending and shears capacities, according to AITIM [18] (AITIM, 2003). The total tests were 30. SAS software was used for fifth percentile determination. With average values of MOE and bending capacity and a temporary load duration factor (0.8) [18] (AITIM, 2003), the bending value was calculated parallel to the fiber design (Fd), and, with this value, the MOR bending design value was calculated.

Shear value was calculated using shear capacity and a 0.5 correction factor [18] to yield the final shear value. Finally, for the deflection, the moment of inertia was used to calculate stiffness to bending [19]. For this case, allowable deformation for roofing systems was used for allowable span determination. In the allowable deformations, house and retail unit roof spaces, which use 360 cm supports, were used as reference. However, in the case of paneled roofs, a 240-cm span was left between supports.

2.7. Floor and Roof Design Values

In order to show the usefulness of the design values, design curves for three values of spacing between I-beams commonly used in Costa Rica is shown: 40, 60 and 80 cm (**Figure 3**). MORc was calculated for the three possible limit states for I-beams: bending, shear, and deformation stiffness and the lowest of the three were selected to be used in the design tables. Different structural uses (**Table 1**) were applied to calculate these values for minimal unit temporary loads established in the Costa Rican Seismic Code [17]. In addition, overloads from 5.0 to 15.0 (in 2.5 MPa increments) were assessed. The same approach [17] as used for floors was used for roof systems. A minimum temporary load of 4 MPa was used and overloads ranging from 2 to 12 MPa (2 MPa increments) considered.

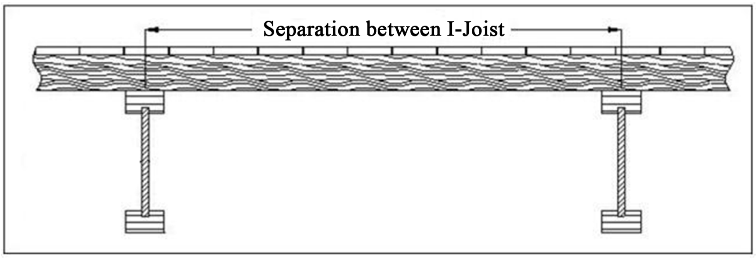

Figure 3. Separation of the Joist during use in floors and roofs.

Table 1. Description of the use of the minimal unit temporary load established by the Costa Rican Seismic Code for use in floor spaces.

Use of the minimal unit temporary load according to Costa Rican Seismic Code	Temporary load (MPa)
Room (room houses, apartments, houses, bedrooms, hotel rooms, buildings for boarding schools, barracks, prisons, correctional facilities, hospitals and the like). Roof deformations less than 5 percent.	2.0
Offices, laboratories, lecture halls, classrooms, and game rooms.	2.5
Cantilevers on public roads (canopies, balconies and the like). Garages and parking (for cars only).	3.0
Stairs, ramps, hallways, passages open to the public. Places of assembly with fixed seating, temples, cinemas, theaters, gyms, etc.	3.5
Meeting places devoid of fixed seats, stadiums, dance halls, libraries, file rooms. Shops, warehouses and factories in good light.	4.5
Shops, warehouses and factories of goods with medium weight.	5.5
Shops, warehouses and factories with heavy goods.	7.0

Source: CFIA [17].

3. Results and Discussion

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3.1. Static Bending Strength and Shear

The average values of flexural strength and shear for the I-joist fabricated with *G. arborea* plywood and laminated-bamboo flange are presented in **Table 2**. It was found an average modulus of rupture (MOR) of 39.4 MPa, while the average of MOE of 17.5 GPa. In relation to shear test it was found that the shear stress at the glue line average is 5.95 MPa and the laminar stress was 6.45 MPa (**Table 2**). Average values were determined from 25 tests.

Comparing the stress value in the shear test (**Table 2**) with other studies [1] [20], it was found that the glue line and laminar stress values are greater than those reported by Barreto [20] with *G. angustifolia* bamboo, which reported a variation from 3.7 to 5.2 MPa using as urea-formaldehyde adhesive, polypropylene and polyvinyl acetate (PVA). The difference found between our study and those reported previously is due to the type of adhesive used in our study, formaldehyde melamine-urea, providing better structural behavior than urea formaldehyde adhesive or PVA. However, López and Correal [1] reported a value of 7.92 MPa in the same mechanical test with phenol-formaldehyde, higher than the value found in the present study, probably influenced again by adhesive.

In relation to the flexure test, the results are compared to the design and materials used by Aschheim *et al*. [3], who tested 2.13 m long I-joists fabricated (with a flange of 7.62 cm × 3.81 cm and a I-joist height of 24.1 cm)

Table 2. Average strength values obtained for I-joist with *Guadua angustifolia* flanges.

Test	Density (Kg/m^3)	MOR (MPa)	MOE (GPa)
Bending	464 (102) [304 - 536]	39.6 (9.9) [21.9 - 58.3]	16.4 (4.0) [8.3 - 18.8]
Shear test	Density (Kg/m^3)	Glue line stress (MPa)	Glue laminar stress (MPa)
	822 (59) [926 - 729]	5.9 (1.6) [3.0 - 9.1]	6.5 (2.6) [3.2 - 9.3]

Note: Values in parentheses are standard deviation and the values in brackets represent the minimum and maximum values.

with bamboo laminated in the flange, but with OSB and plywood in the web. Ascheim *et al*. [3] found a flexural strength of 36 MPa, a MOE of 14 GPa and a shear stress at 1.7 MPa for bamboo OSB and of 0.94 for the same material plywood. These values are slightly lower than those obtained in the present study. In relation to the I-joist designed by Aschheim *et al*. [3], this study's I-joist has a lower height (18.5 cm) and a span of 3.5 m in relation to the Aschheim *et al*. [3] study (24.1 cm in height and 2.13 m in span).

In another study with 18 cm high I-joists, but with *Pinustaeda* and *Eucalyptus dunnii* wood [21], it was found that these species present MOR values of 91 to 102 MPa and MOE of 13 GPa, higher and lower, respectively, to the ones found for laminated bamboo flanges of this study. These differences in the values of MOR and MOE can be attributed to the formation of the web and the flange. Pedrosa *et al*. [21] used OSB and plywood pads (LVL) in the web, unlike this study in which glued laminated bamboo plywood and *G. arborea* webs were used.

Furthermore, the values of MOR and MOE of the bamboo-flanged I-joists with different profiles and qualities of the same flange-dimensioned I-joists, but of *G. arborea* solid wood in flange and plywood again in the web [4] were compared. It was found that bamboo-flanges beams have MOR and MOE values exceeding *G. arborea* I-joist with heights of 10.0, 16.5 and 24.2 cm. Therefore, the 18.5 cm height bamboo flange has more bending resistance than *G. arborea* I-joist with heights greater than 24.2 cm. The relationship between the applied load and deflection in I-joist fabricated with bamboo flanges and *G. arborea* plywood web (**Figure 4**) is noted that the bamboo flanges beams have a lower deformation relative to the *G. arborea* I-joist of any quality and with any dimension. For example, a deformation of 2.0 cm in a bamboo´s flanges I-joist required 650 kg load, but if this beam constructed with solid *G. arborea* wood flanges beam, the required load varies from 350 to 500 kg with same span.

3.2. Design Efforts

I-joists with bamboo flanges have flexural stress value (Fd) of 9.43 MPa and shear (Fv) 4.72 MPa. Comparing these values with I-joists of different qualities ("A" = high quality and "B" = low quality) constructed with *G. arborea* flanges [4] found that bamboo I-joists have a Fd and Fv lower than the ones present in *G. arborea* flanges of "A" quality but higher than those of "B" quality for any height of the I-joist (**Table 3**). With respect to the flexural rigidity (E*I) of bamboo-flanged I-joists, this value was 47.42 MPa, higher than reported by Moya *et al*. [4] for I-joists with solid *G. arborea* wood in the flanges (**Table 3**).

On the other hand, according to the proposed structural classification for the Andean Group countries of the South American region [22], the structural group "C" species (with a basic density of 0.40 to 0.55) present allowable flexural stresses (Fd) of 10.0 MPA and shear (Fv) stresses of 0.8 MPa. The bamboo I-joists satisfy this criteria, exhibiting values of 9.4 and 4.7 MPa, respectively. So the J-joist constructed with bamboo flanges and *G. arborea* plywood web, can be categorized in the structural "C" in the Andean structural classification.

Figure 5(a) shows the maximum allowable span for I-joists with bamboo flanges, for use in flooring with spacing of 40, 60 and 80 cm, commonly used in Costa Rica. For example, I-joists under a load of 30 MPa and a 40 cm spacing between I-joist, have a maximum span of 3.7 m; whereas when using a spacing of 60 cm, the allowable span decreases to 3 m and at 80 cm spacing the span falls to 2.6 m In the case of using these I-joists in roofing (**Figure 5(b)**), with a load of 4 MPa, the permissible span with 40 cm spacing is approximately 7 m, with 60 cm spacing, this decreases to 5.8 m and with 80 cm spacing to 5 m.

4. Conclusion

The results show that it is possible to fabricate I-joists with bamboo *Guadua angustifolia* Kunth in the flange

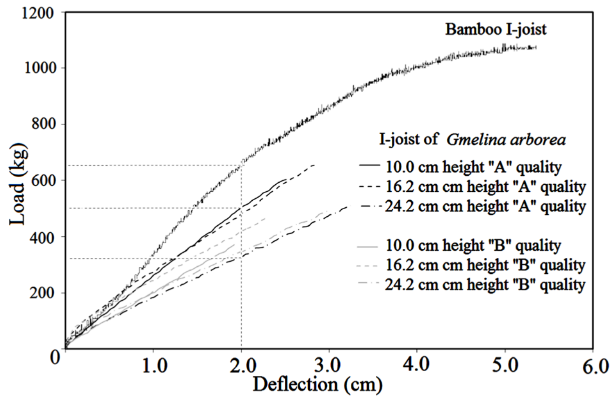

Figure 4. Comparison of the relationship between load vs. deflection for different types of I-joist used for *G. arborea* [4] and I-beams with bamboo flange.

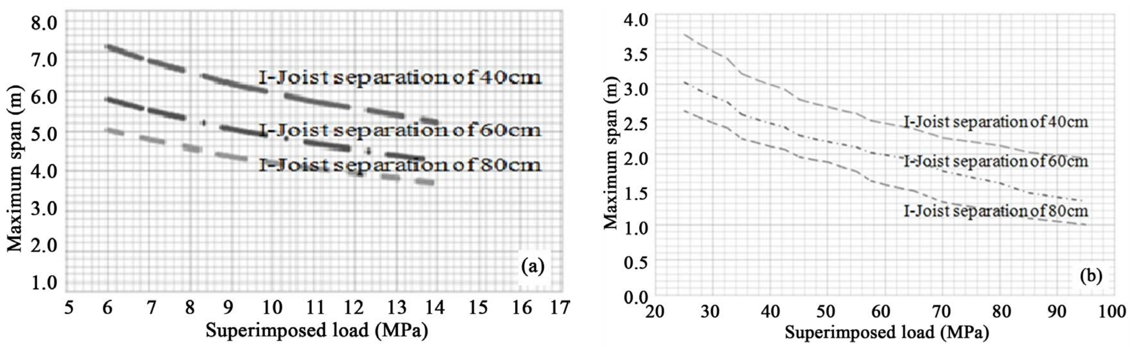

Figure 5. Maximum span in I-joist fabricated with bamboo's flanges for use in (a) flooring and (b) roofing.

Table 3. Design values obtained for the I-beams.

Profile	Quality	Mpp (Kg-m)	Mrup (kg-m)	MORc (MPa)	Fd (MPa)	Fv (MPa)	E*I (kg-cm^2)
I-Joist of bamboo		745	82.3	31	94	47	47.42
Height (cm) in *Gmelina arborea* I-joist							
10.0	A	126	206.7	20.6	148	92	35.89
	B	126	124.8	12.4	68	42	
16.5	A	412	390.8	17.2	119	74	12.10
	B	409	273.2	12.1	60	38	
24.0	A	1244	787.8	16.5	120	75	30.79
	B	1229	592.5	12.4	81	51	

Note: Mpp: when the weight of the beam in kg-cm; Mrup: moment of rupture; MORC: modulus of rupture corrected; Fd: bending stress in kg/cm^2; Fv: shear stress in kg/cm^2; E*I: bending stiffness.

sourced from plantations in Costa Rica and plywood from fast-growing plantations of *Gmelina arborea* in the web. The resulting joists are comparable to structural grade "C" proposed by the Andean Group for structural wood use. The bamboo I-joist can be used in flooring and roofing uses. It was found that maximum span may vary from 2.6 m to 3.7 m in flooring use for 3 MPa of loads, and 5 to 7 meters in 4 MPa in roof loads.

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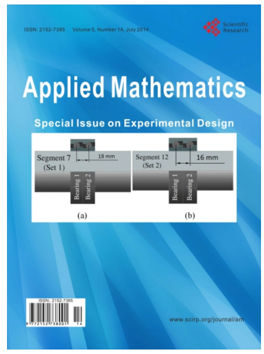
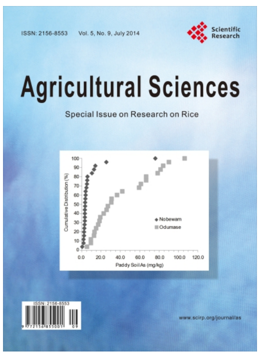
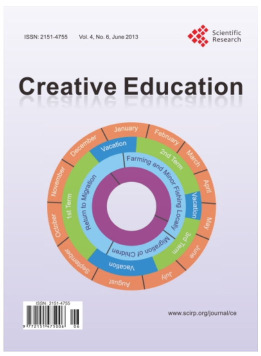
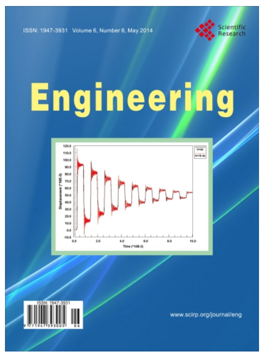
Analytical Chemistry


American Journal of
Plant Sciences
Special Issue on Photosynthesis

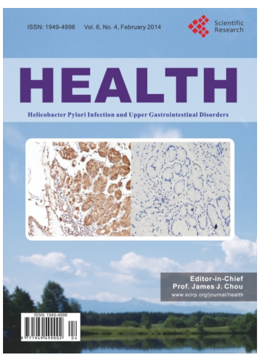

Applied Mathematics
Special Issue on Experimental Design

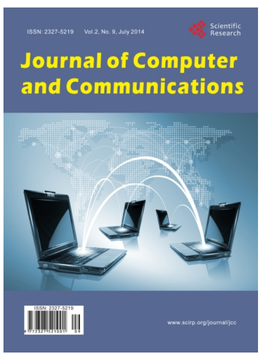

Agricultural Sciences
Special Issue on Research on Rice


Creative Education

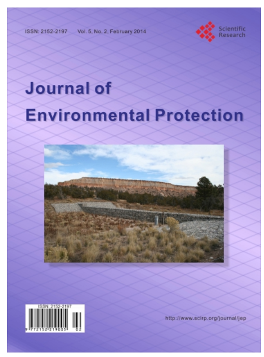

Engineering

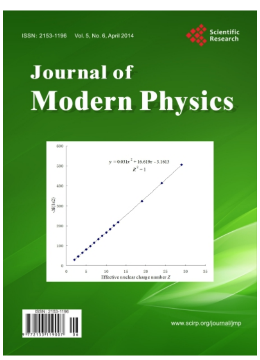

Food and Nutrition Sciences

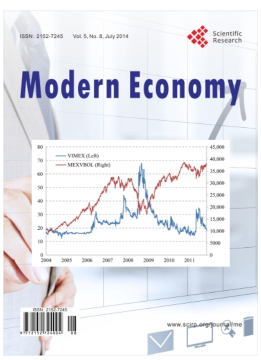

HEALTH
Helicobacter Pylori Infection and Upper Gastrointestinal Disorders
Editor-in-Chief
Prof. James J. Chou


Journal of Computer
and Communications


Journal of Cancer Therapy
Special Issue on Bone Tumor Research


Journal of
Environmental Protection


Journal of
Modern Physics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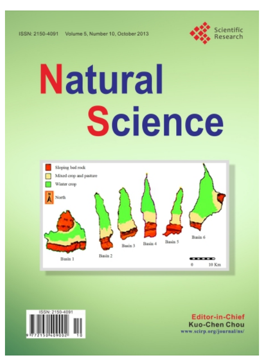
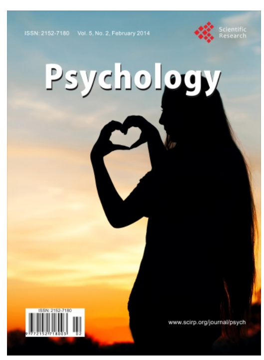

Natural
Science
Editor-in-Chief
Kuo-Chen Chou


Psychology