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A NEW MIX DESIGN METHOD FOR STEEL-FIBER REINFORCED CONCRETE BASED ON ITS RHEOLOGICAL AND FRACTURE BEHAVIOR

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Abstract. Commonly, the design of concrete mix for reinforced structures is based on the definition of consistency (opposition of the material in the fresh state to deformation) and the characteristic compressive strength, considering that the capacity of the tensile behavior is assumed by the steel reinforcement. However, the use of steel fibers as dispersed reinforcement in concrete has led to the development of special documents within structural design codes, lately in date Annex L in the new Eurocode 2, defining steel-fiber reinforced concrete (SFRC) also in flexural strength classes. This fact allows us to consider the fracture behavior of the material, taking into account at the same time its compressive strength and its bending capacity, both in terms of strength, energy absorption capacity, and ductility. Hence the need to develop a SFRC mix design methodology, more adjusted to the real behavior of the composite, which would give rise to more efficient structural elements.

In this communication, a new mix design method for SFRC based on its rheological and fracture behavior is presented. In the fresh state, the target consistency (defined by the rheological parameters of the material) is established. In the hardened state, the target compressive and flexural strength classes are established too, both related through a series of equations obtained using statistical techniques applied to an extensive database of experimental results. From the geometric properties of the fiber (length, diameter and aspect ratio), the volume fraction of steel fiber required to reach the target flexural strength classes is calculated through these equations. Finally, the optimization of the compactness of the composition of the granular skeleton is carried out, which influences the modulus of elasticity and the compressive strength. The results of the experimental validation of the methodology carried out on a laboratory and industrial scale show its relevance and indicate its suitability for the design of SFRC structural elements, which is an added value in concrete technology.

1 INTRODUCTION

The use of steel fibers in concrete provides the material with a remarkable improvement in its mechanical properties, both in terms of residual flexural strength [1] and compressive energy absorption capacity and ductility [2]. This fact allows for approaching its design, considering not only the usual criterion of compressive strength but also taking into account the mentioned aspects.

The development of specific documents within structural design codes dedicated to steel-fiber reinforced concrete (SFRC), such as Annex L of the new Eurocode 2 (EC-2) [3], is highly valuable in this regard. However, these documents do not yet consider that compressive strength and flexural strengths are coupled mechanical properties; in other words, the latter depends to a large extent on the values of the former, as well as the quantity and geometric characteristics of the steel fibers [4]. This fact allows for designing sections of SFRC structural elements with different types of steel reinforcement (passive, active, and encased profiles) from another perspective in which material composition plays a crucial role.

The use of high-flow concrete allows for better wrapping of the reinforcements and fibers due to its higher paste content, resulting in stiffer and stronger interfaces between steel and concrete. The outcome is a composite with higher post-cracking strength, ductility, and energy absorption capacity [5]. Moreover, the success in the structural response depends significantly on the mixture's composition; thus, it is essential to consider methodologies based on the rheological behavior of the concrete-fiber assembly.

This communication presents a new design methodology for SFRC based on the rheological behavior and fracture objectives, driven by a genuine need for research. From initial data, a material has been designed and manufactured, and its results, both at the laboratory and industrial scales, meet the established requirements.

2 MATERIALS AND METHODOLOGY

2.1 SFRC requirements and evaluation of initial data

- Flow behavior: vibrated, pumpable.
- High mechanical stiffness.
- Compressive strength class: C 35/45 (Eurocode 2).
- Minimum flexural strength class: 3b (Annex L, Eurocode 2).

In this research, the steel fibers to be used are ArcelorMittal [6], with the following characteristics:

- Hooked-end steel fiber, HE++ 75/35.
- Ultimate steel wire strength, f_u = 1900 MPa.
- Nominal length, ℓ_f = 35 mm.
- Nominal diameter, d_f = 0.75 mm.
- Aspect ratio, λ = 47.
- Fiber volume fraction, ϕ_f = 0.25-0.38% (20-30 kg).

First, it is evaluated whether the required mechanical performance will be achieved with these initial data; for this purpose, Eqs. (1), (2), and (3) [4] have been used:

$$f_{L\mathrm{k}} = 0.967 + 0.05133\, f_{cu,\mathrm{m}} + 0.019\, \ell_f^* - 0.00066\, \lambda + 126.5\, \phi_f \quad (1)$$

$$f_{R,1\mathrm{k}} = -6.260 + 0.06039\, f_{cu,\mathrm{m}} - 0.171\, \ell_f^* + 0.0518\, \lambda + 715.7\, \phi_f \quad (2)$$

$$f_{R,3\mathrm{k}} = -8.87 + 0.07501\, f_{cu,\mathrm{m}} + 1.058\, \ell_f^* + 0.0562\, \lambda + 655.3\, \phi_f \quad (3)$$

where $\ell_f^* = \frac{\ell_f}{\ell_0 = 30 \text{ mm}} = 1.6$

Initial data introduced in Eqs. (1), (2), and (3) provides the following results:

- $f_{L\mathrm{k}} = 4.4$ MPa.
- $f_{R,1\mathrm{k}} = 2.1$ MPa.

- $f_{R,3\mathrm{k}} = 1.5$ MPa.
- Flexural strength class: 2b.

According to these results, the initial data does not allow reaching the flexural strength class of SFRC. As the type of steel fiber was kept constant (i.e., the geometrical characteristics, ℓ_f^* and λ parameters), only can be modified $f_{cu,\mathrm{m}}$ and ϕ_f. Both appear as statistically significant factors in the flexural behaviour [4], thus being the parameters that have the greatest influence. This consideration is essential because it is not feasible to reach any flexural strength class without considering the compressive strength class associated with: flexural and residual flexural behavior are linked to compressive behavior in SFRC. Moreover, ϕ_f is an important factor to take into account in the residual flexural behavior of the composite. So according to this analysis, it has been selected both a higher compressive strength class C 40/50 and steel-fiber content ϕ_f = 0.6% (47.1 kg/m^3), for reaching the following flexural strengths the SFRC to be design:

- $f_{cu,\mathrm{m}} = 60$ MPa.
- $f_{cu,\mathrm{k}} = 52$ MPa.
- $f_{c,\mathrm{m}} = 50$ MPa.
- $f_{c,\mathrm{k}} = 42$ MPa.
- Compressive strength class: C 40/50.
- $f_{L\mathrm{k}} = 4.8$ MPa.
- $f_{R,1\mathrm{k}} = 4.1$ MPa.
- $f_{R,3\mathrm{k}} = 3.4$ MPa.
- Flexural strength class: 4b.

2.2 SFRC mix design methodology

Understanding the rheological behavior of any concrete is essential for construction industry because it is mixed, poured and placed in a plastic state [8]. For this reason, the SFRC mix design methodology proposed in this research departs from that developed for self-compacting steel-fiber reinforced concrete (SCSFRC) by De La Rosa *et al.* [7], based on the rheological (plastic viscosity, η_e) and mechanical behavior of the material (compressive strength). Considering that the methodology also requires the volume fraction, ϕ_f, and aspect ratio, λ, of the fiber as input data, and both parameters influence not only the rheological behavior but also the mechanical response to flexural loading (together with compressive strength and fiber length, ℓ_f), the method has the necessary versatility to also consider residual flexural strengths as design parameters.

As the fluidity of fresh concrete depends on its rheology it is required that the concrete is not self-compacting but has a high degree of deformability (liquid consistency according to the Abrams cone test). The initial mixture of SCSFRC will be calculated based on the initial water/cement (w/c) and superplasticizer/cement (SP/c) ratios, adjusting the target fluidity through the superplasticizer content.

Next, the paste phase content will be reduced because self-compactability is not required; at this point, the composition of the granular phase (particularly the coarse aggregate) will be optimized to achieve maximum compactness. To achieve this, the modified Toufar model will be used [11, 12]. This optimization will influence the mechanical properties (compressive strength and modulus of elasticity) and environmental and economic sustainability (reducing the carbon footprint and the cost of the composite, due to the decrease of cement paste quantity), respectively.

In this way, the SCSFRC will have the required fluidity for pumping, a high modulus of elasticity, and excellent fracture properties concerning maximum and residual strengths (both in compression and flexural strength). It will also have high energy consumption capacity and notable ductility.

Four different compositions of SFRC have been designed based on the following criteria:

- AM-A1: original design of SCSFRC, reducing the amount of superplasticizer admixture (which influences the yield stress of the paste, τ_{0p}, a rheological parameter governing deformability [9]) to avoid achieving self-compacting behavior. The

composition of the coarse aggregate has been optimized using the modified Toufar model to achieve maximum compactness.
- AM-A2: reduction of cement content and increased limestone powder, which implies a higher amount of superplasticizer due to the high affinity of the mineral addition compared to the admixture. The water content is decreased to maintain the w/c ratio and preserve the design compressive strength. The quantities of fine and coarse aggregate remain unchanged.
- AM-A3: limestone powder quantity is reduced, thereby optimizing the paste content. Volume compensation is achieved by increasing the amount of fine and coarse aggregate while maintaining their proportions to ensure maximum compactness of the granular skeleton.
- AM-A4: cement and water content of AM-A2 and AM-A3 mixes are kept unchanged, but limestone powder is not added. The goal is to achieve the required fluidity of the system through the granular skeleton instead of relying on the superplasticizer. Both fractions of coarse aggregate are maintained to maximize the compactness of the granular skeleton, but with an increased content of both fractions to modify the value of yield stress of SFRC, τ_0 [10].

2.3 Raw materials

The selection of raw materials has taken into account both the quality of materials to carry out a good manufacturing process on an industrial scale and the use of locally available materials, particularly aggregates. The following describes what they are:

- Type I portland cement, CEM I 52.5 R-SR 5 (CEMEX), c.
- Limestone powder as a mineral addition, Betocarb P1-DA (Omya Clariana), LP.
- Local tap water, w.
- Superplasticizer admixture MasterEase 5025 (Master Builders), SP.
- Air occluded reducer admixture MasterCast 212 (Master Builders), AOR.
- Rounded siliceous fine aggregate, 0/4 mm (Hermanos Sierra, C.B.), FA
- Crushed limestone coarse aggregate 6/12 mm and 12/20 mm (Intedhor, S.L.), CA_1 and CA_2, respectively.
- Steel fiber HE++ 75/35 (ArcelorMittal), f.

2.4 Mechanical tests

The measurement of the elastic modulus and Poisson's ratio has been carried out on a cylindrical specimen with dimensions 150×300 mm^2, diameter×height. The compressive strength was also determined using the same geometry and cubic specimens of 100 mm in side. Both tests were conducted on a servo-hydraulic machine Servosis with a capacity of 300 Tn, in load control mode.

The measurement of flexural strength was obtained from a notched prismatic specimen with dimensions 420×100×100 mm^3, length×height×width, sawing a central notch with a depth 1/6 of the height. This test was performed on an servo-hydraulic machine Instron 8805, in displacement control mode, using a 25 kN load cell. Two LVDT devices were used to measure the vertical displacement under the point of load application, and a clip-type device was utilized to measure the crack opening mouth of the notch.

3 RESULTS AND DISCUSSION

3.1 Laboratory scale

The composition and characterization in the fresh state (slump flow test) of the four SFRC mix designs made at the laboratory scale are shown in Table 1. Tables 2 and 3 include the results of the mechanical characterization carried out for each of the four laboratory-scale SFRC mix designs, as well as their classification into strength classes for both compression and flexural strength. Once the most suitable mix is selected, it will be manufactured on an industrial scale to verify and/or make necessary adjustments before a prefabrication process.

Table 1: Mix design composition of SFRC at laboratory scale (batches 0.023 m^3).

	[kg/m^3]			
	AM-A1	AM-A2	AM-A3	AM-A4
c	442	380	380	380
w	204	176	182	175
SP	2.652	5.304	3.800	3.800
AOR	1.518	1.518	1.518	1.518
LP	170	290	90	0
FA	800	800	950	720
CA_1	483	483	525	770
CA_2	207	207	225	330
f	47.1	47.1	47.1	47.1
Slump (cm)	16.5	17.0	19.0	16.5
w/c	0.46	0.46	0.48	0.46
SP/c	0.006	0.014	0.010	0.010
AOR	1.5% (vol.)	1.5% (vol.)	1.5% (vol.)	1.5% (vol.)
ϕ_f	0.6% (vol.)	0.6% (vol.)	0.6% (vol.)	0.6% (vol.)

Table 2: Mechanical properties of the mix designs manufactured in the laboratory (I).

	AM-A1	AM-A2	AM-A3	AM-A4
E [GPa]	37.4 (0.3)	41.4 (0.0)	44.7 (2.4)	43.0 (2.6)
ν	0.21 (0.00)	0.22 (0.01)	0.23 (0.00)	0.22 (0.01)
$f_{c,m}$ [MPa]	59.7 (0.3)	65.6 (0.5)	65.7 (1.7)	63.8 (1.0)
$f_{c,k}$ [MPa]	51.7	57.6	57.7	55.8
$f_{cu,m}$ [MPa]	61.9 (1.5)	68.9 (3.0)	67.4 (3.4)	67.9 (0.9)
$f_{cu,k}$ [MPa]	53.9	60.9	59.4	59.9
Class (EC-2)	C 40/50	C 50/60	C 45/55	C 45/55

Table 3: Mechanical properties of the mix designs manufactured in the laboratory (II).

	AM-A1	AM-A2	AM-A3	AM-A4
σ_m [MPa]	6.6 (1.0)	5.8 (0.7)	6.7 (0.3)	6.8 (0.0)
$f_{L,m}$ [MPa]	5.5 (0.2)	5.1 (–)	6.3 (0.1)	6.8 (0.0)
$f_{L,k}$ [MPa]	5.1	5.1	6.1	6.7
$f_{R1,m}$ [MPa]	6.0 (1.0)	5.9 (–)	6.4 (0.1)	5.1 (1.0)
$f_{R1,k}$ [MPa]	4.1	5.9	6.2	3.1
$f_{R3,m}$ [MPa]	4.6 (0.1)	2.7 (–)	6.0 (0.3)	4.8 (0.9)
$f_{R3,k}$ [MPa]	4.4	2.7	5.5	3.0
Class (EC-2)	4 d	5 a	6 c	3 c

Figure 1 shows the stress-crack opening curves resulting from the three-point bending tests conducted on prismatic specimens 420×100×100 mm^3, length×height×width, (with a central notch of depth 1/6 of the height) for each of the four SFRC mix designs made at the laboratory scale.

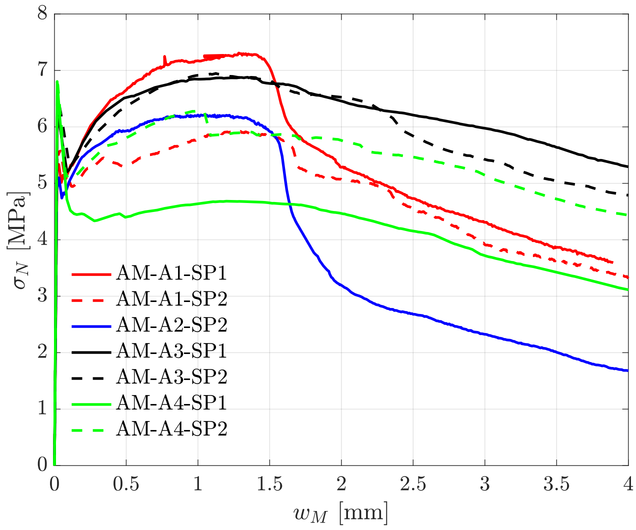

Figure 1: Mechanical characterization. Three point bending test curves at the laboratory scale, in small prism (SP) 420×100×100 mm^3, length×height×width, with a central notch of depth 1/6 the height.

According to the results shown in the Tables 2 and 3 and Fig. 1, all four designs meet the selected compression strength class; furthermore, in all cases, the values of the elastic modulus are very high, exceeding 40 GPa in three designs (AM-A2, AM-A3, AM-A4). Regarding the response to flexural strength, mix designs AM-A1 and AM-A3 exceed the chosen strength class. Therefore, one of these two designs will be the one we select as the final choice.

The choice of AM-A3 over AM-A1 mix design is based on the following criteria:

- Optimum content in paste.
- Optimum economic and environmental sustanaibility criteria.
- High elastic modulus and Poisson coefficient: 44.7 GPa, 0.23, respectively.

- High compressive class: C45/55
- High flexural class: 6c

3.2 Industrial scale

The composition and characterization in the fresh state through slump flow test of the two batches of the selected SFRC mix design (A3) made on an industrial scale are shown in Table 4. On this scale, batches of 0.5 m^3 each have been produced. The protocol for introducing raw materials and mixing times is the same as that followed at the laboratory scale.

Table 4: Mix design composition of AM-A3 at factory scale (batches AM-A3-a and AM-A3-b 0.5 m^3).

	[kg/m^3]	
	AM-A3-a	AM-A3-b
c	380	380
w	182	182
SP	3.800	3.040
AOR	1.518	1.518
LP	90	90
FA	950	950
CA_1	525	525
CA_2	225	225
f	47.1	47.1
Slump (cm)	24.5 cm	13.0 cm
w/c	0.48	0.48
SP/c	0.010	0.008
AOR	1.5% (vol.)	1.5% (vol.)
ϕ_f	0.6% (vol.)	0.6% (vol.)

The only difference between both is the quantity of superplasticizer. This variation has been carried out to test the effectiveness of the admixture when manufacturing a larger volume of SFRC. As observed, a slight decrease in the superplasticizer content (from $SP/c = 0.010$ to 0.008) leads to a significant variation in fluidity in terms of deformability or consistency in the Abrams cone test (from 24.5 cm to 13.0 cm, respectively). This issue is very important to consider in the industrial-scale production of large volumes of material.

Figure 2 shows the flexural stress-crack mouth opening displacement curves, σ_N-w_M, resulting from the three-point bending tests.

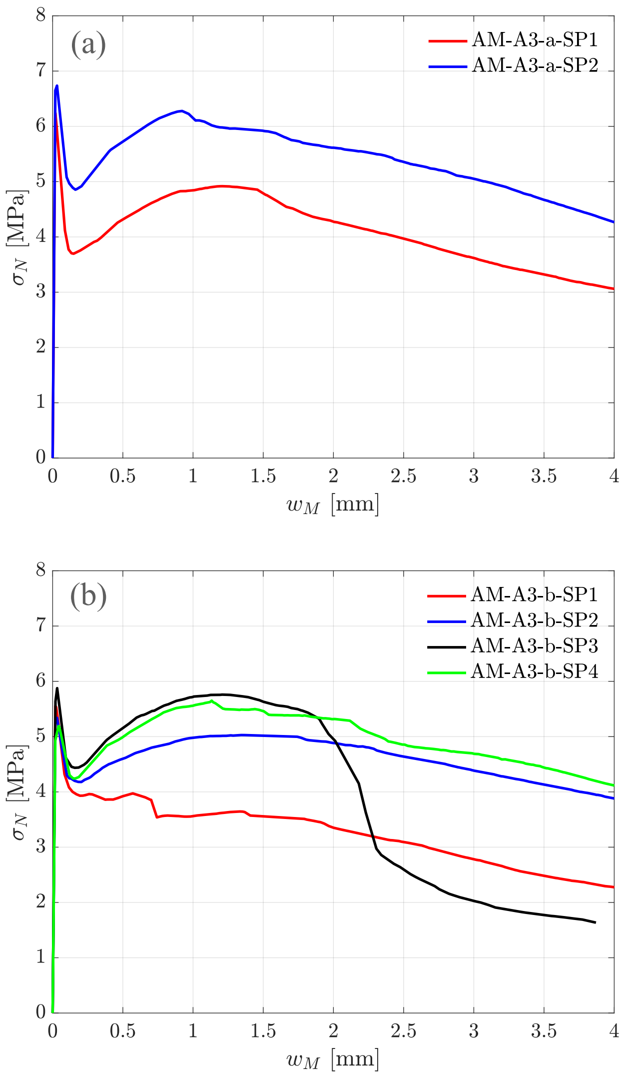

Figure 2: Mechanical characterization. Three point bending test curves at the factory scale: (a) AM-A3-a; (b) AM-A3-b, both in small prism (SP) 420×100×100 mm^3, length×height×width, with a central notch of depth 1/6 the height.

After conducting the tests, the fiber count was performed in the two sections of the broken specimens, establishing nine quadrants to assess the homogeneity in their distribution and the potential influence of the content and average orientation angle on the residual flexural strengths for different crack opening values.

The same analysis was conducted with the specimens defined at the laboratory scale.

Tables 5 and 6 show the results of the mechanical characterization carried out for the two industrial-scale mixtures of the selected SFRC mix design (A3), as well as their classification into strength classes for both compression and flexural strength.

It can be observed that AM-A3-a mix does not reach the target design strength for $f_{R1,k}$ but it does exceed the design strength for $f_{R3,k}$. However, the minimum initial design requirement is 3b, so we can consider the objective fulfilled. As for AM-A3-b mix, despite the effect of vibration, a lower deformation in terms of consistency (due to the lower content of superplasticizer admixture) may result in reduced workability of the material, leading to a poorer and less uniform distribution of fibers during mixing and, consequently, in the distribution of the fiber in the sections of the specimens. This primarily penalizes the value of $f_{R3,k}$, as can be observed. Regarding the values of the elastic modulus and compressive strengths, both mixtures exceed the initial design values.

In summary, based on the analysis carried out, the mix AM-A3-a is chosen to be manufactured on a larger industrial scale using a specific prefabrication process that meets the initial requirements. Thus, the methodology presented in this communication demonstrates its validity for the design of SFRC based on target performance, both rheological and mechanical criteria, followed by its subsequent manufacturing on an industrial scale.

Table 5: Mechanical properties of the mix design selected AM-3 manufactured in the factory (I).

	AM-A3-a	AM-A3-b
E [GPa]	40.4 (-)	40.5 (3.3)
ν	0.28 (-)	–
$f_{c,m}$ [MPa]	62.1 (-)	61.7 (1.2)
$f_{c,k}$ [MPa]	54.1	53.7
$f_{cu,m}$ [MPa]	66.2 (1.1)	62.3 (2.4)
$f_{cu,k}$ [MPa]	58.2	53.3
Class (EC-2)	C 45/55	C 40/50

Table 6: Mechanical properties of the mix design selected AM-3 manufactured in the factory (II).

	AM-A3-a	AM-A3-b
σ_m [MPa]	6.6 (0.4)	5.6 (0.3)
$f_{L,m}$ [MPa]	5.5 (0.5)	5.5 (0.3)
$f_{L,k}$ [MPa]	4.6	5.0
$f_{R1,m}$ [MPa]	5.0 (1.0)	4.7 (0.6)
$f_{R1,k}$ [MPa]	3.0	3.7
$f_{R3,m}$ [MPa]	4.7 (1.0)	3.8 (1.1)
$f_{R3,k}$ [MPa]	2.7	1.8
Class (EC-2)	3 c	3.5 a

4 CONCLUSIONS

A novel mix design methodology for SFRC based on target rheological and fracture behavior is present. From initial data and raw materials, several compositions of SFRC have been designed and, next, manufactured.

The initial step at the laboratory-scale manufacturing (low volume of batch) and testing is the main reference to analyze and select the most suitable mix; after that, the mix design chosen has to be manufactured on an industrial scale (high volume of batch) to verify and make adjustments before starting a precasting process.

Results obtained at the laboratory and industrial scales meet the established requirements, both rheological behavior in the fresh state and mechanical performance (compressive and flexural strength classes) in the hardened state.

Finally, the methodology developed demonstrates its validity and usefulness for designing SFRC based on target performance (rheological and mechanical criteria) and its subsequent manufacturing on an industrial scale.

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NOMENCLATURE

	Mechanical parameter
E	Young´s modulus
ν	Poisson´s ratio
$f_{c,m}$	Mean compressive strength (cylinder)
$f_{c,k}$	Characteristic compressive strength (cylinder)
$f_{cu,m}$	Mean compressive strength (cube)
$f_{cu,k}$	Characteristic compressive strength (cube)
σ_m	Flexural strength
$f_{L,m}$	Mean flexural strength (proportionality limit)
$f_{L,k}$	Characteristic flexural strength (proportionality limit)
$f_{R1,m}$	Mean residual flexural strength (w_M = 0.5 mm)
$f_{R1,k}$	Characteristic residual flexural strength (w_M = 0.5 mm)
$f_{R3,m}$	Mean residual flexural strength (w_M = 2.5 mm)
$f_{R3,k}$	Characteristic residual flexural strength (w_M = 2.5 mm)
w_M	Crack mouth opening displacement

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