# On F-contractions: A survey

Nicola Fabiano, Zoran Kadelburg, Nikola Mirkov, Vesna Šešum Čavić and Stojan Radenović

**Abstract.** D. Wardowski proved in 2012 a generalization of Banach Contraction Principle by introducing $F$-contractions in metric spaces. In the next ten years, a great number of researchers used Wardowski's approach, or some of its modifications, to obtain new fixed point results for single- and multivalued mappings in various kinds of spaces. In this review article, we present a survey of these investigations, including some improvements, in particular concerning conditions imposed on function $F$ entering the contractive condition.

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## 1. Introduction and preliminaries

The year 2022 marks the 100th anniversary of the publication (in [31]) of Banach Contraction Principle (or Banach Fixed Point Theorem), the milestone of Metric Fixed Point Theory. Let us recall the formulation of this fundamental theorem:

**Theorem 1.1.** [31] *If $T$ is a mapping from a complete metric space $(X, d)$ into itself and if there is a constant $\lambda \in [0, 1)$ such that for every $x, y$ from $X$,*

$$d(Tx, Ty) \leq \lambda d(x, y) \tag{1.1}$$

*holds, then there exists exactly one point $z \in X$ such that $T(z) = z$. Moreover, for each point $x_0 \in X$, the iterative sequence $\{x_n\}$ defined by $x_n = Tx_{n-1}$, $n \in \mathbb{N}$ converges to $z$.*

The mapping $T : X \to X$ satisfying (1.1) is called a contraction. Among other things, Banach used his theorem to solve a special type of integral equations.

*Remark* 1.2. Actually, this result appeared two years earlier in Banach's Ph.D. Thesis (written in Polish) at L'vov University. However, it did not become widely known until its publication in the journal Fundamenta Mathematica.

Starting from 1922, a large number of mathematicians tried to generalize this famous theorem. These generalizations went in two main directions:

(a) The known axioms of metric space $(X, d)$ were modified and so a lot of new spaces, so-called generalized metric spaces, were introduced. We mention just some of them: $b$-metric spaces, partial metric spaces, metric-like spaces, cone metric spaces, $G$-metric spaces, rectangular metric spaces, etc.

(b) Condition (1.1) was replaced by various other conditions that generalize the condition of contraction.

There were also a lot of attempts which combined both directions.

In this review, we talk about a special generalization of Banach's result, which was introduced in 2012 by the Polish mathematician Darius Wardowski [150] (note that it is now the 10th anniversary of this result). This generalization is of direction (b).

Namely, Wardowski considered mappings $F : (0, +\infty) \to \mathbb{R}$ that satisfy the following conditions:

(F1) $F$ is a strictly increasing function;

(F2) A sequence $t_n \in (0, +\infty)$ converges to zero if and only if $F(t_n) \to -\infty$ as $n \to +\infty$;

(F3) $\lim\limits_{t\to 0^+} t^k F(t) = 0$ for some $k \in (0, 1)$.

Wardowski denoted by $\mathcal{F}$ the collection of mappings $F : (0, +\infty) \to \mathbb{R}$ that satisfy the conditions (F1), (F2) and (F3). Using such functions, he introduced a new type of contraction in a given metric space in the following way:

**Definition 1.3.** Let $F \in \mathcal{F}$ and let $T$ be a mapping from a metric space $(X, d)$ into itself. If there is a positive number $\tau$ such that for all $x, y \in X$ for which $d(Tx, Ty) > 0$,

$$\tau + F(d(Tx, Ty)) \leq F(d(x, y)) \tag{1.2}$$

holds, then the mapping $T$ is called an F-contraction.

The main result of D. Wardowski was the following

**Theorem 1.4.** *Each $F$-contraction $T$ on a complete metric space $(X, d)$ has a unique fixed point. Moreover, for each $x_0 \in X$, the corresponding Picard sequence $\{T^n x_0\}$ converges to that fixed point.*

Obviously, taking $F(t) = \log t$ and $\tau = \log(1/\lambda)$, $\lambda \in (0, 1)$ the condition (1.2) reduces to (1.1), i.e., Theorem 1.4 is a generalization of Theorem 1.1. Moreover, by an example, Wardowski showed that this generalization was genuine (see further Example 2).

This nice result inspired dozens of mathematicians to try to obtain new results by:

1. applying similar idea in various other spaces (among them those mentioned under (a));
2. modifying the contractive condition (1.2) in various ways;
3. modifying conditions (F1)–(F3) for the function $F$.

In this survey, we present briefly some of these attempts, together with some modifications and improvements, in particular concerning properties (F1)–(F3). A review treating some other aspects of these problems can be found in [77].

## 2. A modification of Wardowski's theorem and its proof

First of all, we illustrate relationship between the properties (F1)–(F3).

*Example.* Consider the following functions that map $(0,+\infty)$ into $\mathbb{R}$: $F_1(x) = e^x$, $F_2 = -\dfrac{1}{x}$, $F_3(x) = \dfrac{x-1}{x}$, $F_4(x) = x^x$, $F_5(x) = \log x$, $F_6(x) = -\dfrac{1}{x^{1/n}}$, $n \in \mathbb{N}$, $F_7(t) = t + \log t$. Then:

1. $F_1$ satisfies (F1) and (F3) but not (F2);
2. $F_2$ and $F_3$ satisfy (F1) and (F2) but not (F3);
3. $F_4$ satisfies (F3) but not (F1) and (F2);
4. $F_5$, $F_6$ and $F_7$ satisfy all three properties.

Now we list some properties of a function $F$ that follow just from property (F1):

1. $F$ is continuous almost everywhere.
2. At each point $r \in (0,+\infty)$ there exist its left and right limits $\lim\limits_{t\to r^-} F(t) = F(r^-)$ and $\lim\limits_{t\to r^+} F(t) = F(r^+)$. Moreover, for the function $F$ one of the following two properties holds: $F(0^+) = m \in \mathbb{R}$ or $F(0^+) = -\infty$.
3. Property (F2) is equivalent to
   (F2′) $F(0^+) = -\infty$, as well as to
   (F2″) $\inf_{t\in(0,+\infty)} F(t) = -\infty$.

For more details see [22], [118].

We recall the following two properties of sequences in metric spaces that have often been used, sometimes implicitly, in proving fixed point results (see, e.g., [38, 53, 82, 91, 146, 147, 148, 149] for the first property and [113, 146, 147, 148, 149] for the second one).

**Lemma 2.1.** *Let $\{x_n\}$ be a Picard sequence of a self-map $T$ in a metric spaces $(X,d)$ (i.e., $x_n = Tx_{n-1}$, $n \in \mathbb{N}$). If*

$$d(x_{n+1}, x_n) < d(x_n, x_{n-1}) \tag{2.1}$$

*holds for each $n \in \mathbb{N}$, then $x_n \neq x_m$ whenever $n \neq m$.*

**Lemma 2.2.** *Let $\{x_n\}$ be a sequence in a metric space $(X,d)$ such that $d(x_n, x_{n+1}) \to 0$ as $n \to +\infty$. If $\{x_n\}$ is not a Cauchy sequence then there* *exist* $\varepsilon > 0$ *and two sequences* $\{m_k\}$ *and* $\{n_k\}$ *of positive integers, satisfying* $n_k > m_k > k$*, such that the following sequences tend to* $\varepsilon^+$ *as* $k \to +\infty$*:*

$$d(x_{m_k}, x_{n_k}), \quad d(x_{m_k}, x_{n_k+1}), \quad d(x_{m_k-1}, x_{n_k}),$$
$$d(x_{m_k-1}, x_{n_k+1}), \quad d(x_{m_k+1}, x_{n_k+1}), \quad \dots$$

We now formulate an improved version of Wardowski's result that is given in [112, Corollary 2]. Our proof is shorter than the original one, since it uses Lemmas 2.1 and 2.2 (for the sake of brevity, we treat just the basic case $\alpha = 1$ of [112, Theorem 5]).

**Theorem 2.3.** *Let* $(X, d)$ *be a complete metric space and* $T$ *be a self-mapping on* $X$*. Assume that there exist a strictly increasing function* $F : (0, +\infty) \to \mathbb{R}$ *and* $\tau > 0$ *such that* (1.2) *holds for all* $x, y \in X$ *with* $Tx \neq Ty$*. Then* $T$ *has a unique fixed point in* $X$*.*

*Proof.* Let $x_0 \in X$ be arbitrary, let $\{x_n\}$ be the corresponding Picard sequence defined by $x_n = Tx_{n-1}$, $n \in \mathbb{N}$, and denote $d_n = d(x_{n-1}, x_n)$. We can assume that $d_n > 0$ (i.e., $x_{n-1} \neq x_n$) for each $n \in \mathbb{N}$ (otherwise there is nothing to prove).

Putting $x = x_{n-1}$, $y = x_n$ in the condition (1.2), we get that

$$\tau + F(d_{n+1}) \leq F(d_n), \tag{2.2}$$

and hence (using (F1)) $d_{n+1} < d_n$ for each $n \in \mathbb{N}$. It follows by Lemma 2.1 that $x_n \neq x_m$ whenever $n \neq m$. Also, the sequence $\{d_n\}$ must converge to some $d \geq 0$. If $d > 0$, then, passing to the limit when $n \to +\infty$ in (2.2), it follows that $\tau + F(d^+) \leq F(d^+)$ which is in contradiction with $\tau > 0$. Hence,

$$\lim_{n \to +\infty} d_n = 0. \tag{2.3}$$

Suppose now that $\{x_n\}$ is not a Cauchy sequence and consider the sequences $\{m_k\}$ and $\{n_k\}$ that satisfy conditions as in Lemma 2.2. Since $n_k > m_k$, it follows that $x_{m_k} \neq x_{n_k}$, hence we can use contractive condition (1.2) with $x = x_{n_k}$ and $y = x_{m_k}$. We obtain that

$$\tau + F(d(x_{n_k+1}, x_{m_k+1})) \leq F(d(x_{n_k}, x_{m_k})).$$

Passing to the limit as $k \to +\infty$, using Lemma 2.2 and the mentioned property (2) of the increasing function $F$, we get that

$$\tau + F(\varepsilon^+) \leq F(\varepsilon^+),$$

which is in contradiction with $\tau > 0$. Hence, $\{x_n\}$ is a Cauchy sequence and, since $(X, d)$ is complete, it converges to some $x^* \in X$.

Observe now that the contractive condition (1.2) (where $F$ satisfies the property (F1)) implies that the mapping $T$ is continuous. Hence, it follows in a routine way that $x^*$ is a unique fixed point of $T$. $\square$

*Remark* 2.4. Note that the case (2.3) can only take place if $F(0^+) = -\infty$. Indeed, if $d = 0$, then it follows from (2.2) that $\tau + F(0^+) \leq F(0^+)$, which is impossible if $F(0^+)$ is finite. It means that condition (F2) for the function $F$ is implicitly contained in the formulation of Theorem 2.3. In other words, there is no mapping $T$ which satisfies Wardowski's condition (1.2) with function $F$ satisfying (F1) and not satisfying (F2). Hence, no essentially new results can be obtained by using functions $F$ satisfying just (F1). Bearing this in mind, we will formulate our further results assuming both properties (F1) and (F2).

We recall here the original Wardowski's example that shows that his result is more general than the Banach's one.

*Example.* [150, Example 2.1] Consider the set $X = \{x_n \mid n \in \mathbb{N}\}$ where $x_n = \sum_{k=1}^{n} k = \frac{1}{2}n(n+1)$, equipped with the standard metric given by $d(x,y) = |x-y|$, $x, y \in X$. Then, $(X,d)$ is a complete metric spaces. Let $T : X \to X$ be defined by $T(x_1) = x_1$ and $T(x_n) = x_{n-1}$, $n > 1$. It is easy to see that Banach's condition (1.1) is not satisfied, but Wardowski's condition (1.2) holds with $\tau = 1$ and $F(t) = t + \ln t$. For details see [150].

The next example shows that Theorem 2.3 is a genuine generalization of Theorem 1.4.

*Example.* [112, Example 1] Let $X = \{a_n \mid n \in \mathbb{N}\} \cup \{b\}$ and $d : X \times X \to [0,+\infty)$ is given by $d(a_n,a_n) = d(b,b) = 0$, $n \in \mathbb{N}$ and $d(a_n,a_{n+p}) = d(a_{n+p},a_n) = d(a_n,b) = d(b,a_n) = \frac{1}{n}$ for $n, p \in \mathbb{N}$. Obviously, $(X,d)$ is a complete metric space. Let $T : X \to X$ be given by $Ta_n = a_{n+1}$, $n \in \mathbb{N}$ and $Tb = b$. It is shown in [112] that $T$ cannot satisfy conditions of Theorem 1.4 with any function $F \in \mathcal{F}$, but it satisfies condition of Theorem 2.3 with $\tau \le 1$ and $F(t) = -\frac{1}{t}$ (note that this function does not satisfy the property (F3)). For details see [112].

*Remark* 2.5. The following result was proved in [112] as Theorem 6.

*Let $(X,d)$, $T$ and $F$ satisfy the conditions of Theorem* 2.3*, except that, instead of* (F1)*, $F$ is supposed to be continuous and satisfy condition* (F2)*. Then the same conclusion holds.*

By an example (see [112, Example 2]), it was shown that this result was essentially different from Theorem 2.3, i.e., there exists a mapping $T$ in a metric space $(X,d)$ which does not satisfy conditions of Theorem 2.3, but which satisfies conditions presented in this remark and which has a unique fixed point.

## 3. Some generalizations

### 3.1. Common fixed points

Let $(X,d)$ be a metric space and $T, S$ be two self-mappings on $X$. Recall that if $T(x) = S(x) = y$ then $x$ is called a coincidence point of $T$ and $S$, and $y$ is said to be their point of coincidence. If, moreover, $y = x$ then $x$ is called a common fixed point of $T$ and $S$. In order to obtain a Wardowski-type version of the famous Jungck theorem [72], the authors of [2] called $T$ an $F$-contraction with respect to $S$ if there exists a function $F$ and $\tau > 0$ such that

$$\tau + F(d(Tx,Ty)) \le F(d(Sx,Sy)) \tag{3.1}$$

holds for all $x, y \in X$ satisfying $Tx \neq Ty$. They proved some coincidence and common fixed point results for a pair of mappings acting in ordered metric spaces.

For the sake of simplicity, we formulate these results here without using ordering. Again, just conditions (F1) and (F2) are used and the proof is much shorter because Lemmas 2.1 and 2.2 are used.

**Theorem 3.1.** *Let $(X, d)$ be a complete metric space and $T, S$ be two self-mappings on $X$, such that $T(X) \subseteq SX$, one of these subsets being closed. If $T$ is an $F$-contraction with respect to $S$, where the function $F$ satisfies conditions* (F1) *and* (F2)*, then they have a unique point of coincidence. Moreover, if $T$ and $S$ are weakly compatible (i.e., if they commute at their coincidence points), then they have a unique common fixed point.*

*Proof.* The condition (3.1), together with property (F1), immediately imply that $d(Tx, Ty) < d(Sx, Sy)$ if $Tx \neq Ty$. Further, let $x_0 \in X$ be arbitrary and let the respective Picard-Jungck sequence be defined by

$$y_n = Tx_n = Sx_{n+1}, \quad \text{for } n \in \mathbb{N} \cup \{0\}.$$

Then, using property (F1), it follows that $d(y_n, y_{n+1}) < d(y_{n-1}, y_n)$ if $y_n \neq y_{n+1}$. Now, again, by using Lemmas 2.1, and 2.2 it easily follows that $\{y_n\}$ is a Cauchy sequence. The rest of the proof is standard. □

Results on coincidence and common fixed points under $F$-contractions were also obtained in [14, 39, 40, 141, 142].

### 3.2. Property (P)

Denote by $Fix(T)$ the set of fixed points of a self-map $T$ in a metric space $(X, d)$. Recall that it is said that $T$ satisfies property (P) if $Fix(T^n) = Fix(T)$ holds for each $n \in \mathbb{N}$ (here $T^n$ denotes the $n$-th iterate of the mapping $T$). It is easy to prove the following assertion.

**Proposition 3.2.** *Let $T$ be a self-map in a metric space $(X, d)$ satisfying condition* (1.2) *with function $F$ satisfying* (F1) *and* (F2)*. Then $T$ has the property* (P)*.*

*Proof.* Since $T$ satisfies the condition (1.2), then so does $T^n$ for each $n \in \mathbb{N}$. Indeed, for $x, y \in X$,

$$F(d(T^n x, T^n y)) \leq F(d(T^{n-1}x, T^{n-1}y)) - \tau \leq \cdots$$

$$\leq F(d(x, y)) - n\tau \leq F(d(x, y)) - \tau.$$

Hence, if $T^n x \neq T^n y$, then $T^{n-1}x \neq T^{n-1}y$, ..., and condition (1.2) holds for $T^n$. By Theorem 2.3, $T^n$ has a unique fixed point, and since, obviously, $Fix(T) \subseteq Fix(T^n)$, it follows that property (P) is satisfied. □

A result about the property (P) for $F$-contractions was also obtained in [2].

### 3.3. Generalized contraction

The following result is an improvement of [152, Theorem 2.4]. Its proof can be also made shorter, similarly as in some earlier mentioned cases.

**Theorem 3.3.** *Let* $(X, d)$ *be a complete metric space and* $T$ *be a self-map in* $X$ *satisfying that*

$$\tau+F(d(Tx,Ty)) \leq F\left(\max\left\{d(x,y), d(x,Tx), d(y,Ty), \frac{d(x,Ty)+d(y,Tx)}{2}\right\}\right) \tag{3.2}$$

*holds for some* $\tau > 0$, *some function* $F : (0,+\infty) \to \mathbb{R}$ *satisfying* (F1) *and* (F2), *and all* $x, y \in X$ *satisfying* $d(Tx, Ty) > 0$. *If* $T$ *or* $F$ *is continuous, then* $T$ *has a unique fixed point.*

Further types of generalized $F$-contractions were treated in [3, 9, 23, 26, 27, 32, 33, 35, 44, 51, 54, 61, 62, 71, 76, 80, 88, 92, 106, 108, 109, 111, 115, 121, 122, 123, 125, 130, 135, 136, 137, 140, 143, 144, 151].

### 3.4. Best proximity points

In [37], the authors obtained some results concerning so-called best proximity points of non-self mappings in a complete metric space. We note here just that their Theorems 3.1, 3.2 and 3.3 remain true when just conditions (F1) and (F2) are imposed on the function $F$, and that the proofs of these results can be made much shorter by using Lemmas 2.1 and 2.2, as was done here in the case of Theorem 2.3.

Other results on best proximity points using $F$-contractions were obtained in [103].

### 3.5. Results in $b$-metric spaces

Recall that a triplet $(X, d, s)$ is called a $b$-metric space if $X$ is a non-empty set, $s \geq 1$ is a given real number and $d : X \times X \to [0, +\infty)$ satisfies axioms of a metric spaces, but with the triangular inequality replaced by the condition

$$d(x, z) \leq s[d(x, y) + d(y, z)]$$

for all $x, y, z \in X$.

Results about fixed points in $b$-metric spaces using Wardowski-type conditions were obtained in several papers. We note here that most of these results can be obtained with weaker assumptions on the function $F$. For example, it is the case for a common fixed point result [97, Theorem 1] for four mappings which was proved with weaker assumptions in [154].

We present also another kind of result, obtained by Suzuki in [138], where different assumptions are imposed on the function $F$ (note that (F1) is here not used).

**Theorem 3.4.** [138, Theorem 23] *Let* $(X, d, s)$ *be a complete $b$-metric space and* $T$ *be a self-map on* $X$. *Assume that there exist* $\tau > 0$ *and a function* $F : (0, +\infty) \to \mathbb{R}$ *satisfying* (F2) *such that* (1.2) *holds for all* $x, y \in X$ *with* $Tx \neq Ty$. *Then* $T$ *has a unique fixed point.*

Some other papers where $F$-contractions in $b$-metric spaces were investigated are [13, 15, 45, 50, 74, 75, 84, 86, 101, 107, 110].

### 3.6. Multivalued mappings

Investigation of fixed points of multivalued mappings started in 1969 with the work [94] of Nadler. After 2012, a lot of researchers attempted to apply Wardowski's approach to such problems in various spaces—see, e.g. [1, 4, 5, 6, 7, 12, 18, 19, 20, 24, 25, 29, 41, 46, 48, 58, 60, 63, 68, 69, 70, 73, 81, 83, 89, 95, 98, 105, 116, 119, 129, 131, 132, 138, 153]. We present here just one of the basic results of this kind.

Let $(X, d)$ be a metric space, $CB(X)$ be the family of its nonempty, closed and bounded subsets, and $K(X)$ the family of its nonempty compact subsets. Recall that the Hausdorff-Pompeiu metric on $CB(X)$ is the function $H : CB(X) \times CB(X) \to [0, +\infty)$ defined for $A, B \in CB(X)$ by

$$H(A, B) = \max \left\{ \sup_{x \in A} d(x, B), \sup_{y \in B} d(y, A) \right\}.$$

The following is Theorem 2.2 in [19].

**Theorem 3.5.** *Let $(X, d)$ be a complete metric spaces and $T : X \to K(X)$ be a (multivalued) mapping satisfying*

$$\tau + F(H(Tx, Ty)) \leq F(d(x, y))$$

*for some $\tau > 0$ and $F : (0, +\infty) \to \mathbb{R}$ satisfying conditions* (F1), (F2) *and* (F3), *and for all $x, y \in X$ with $H(Tx, Ty) > 0$. Then $T$ has a fixed point, i.e., there exists $x^* \in X$ such that $x^* \in Tx^*$.*

An open question (which we state at the end of this article) is whether, like in a single-valued case, this result remains valid if just assumptions (F1) and (F2) are imposed on the function $F$.

### 3.7. Some other areas of research

The following is the list of other areas where $F$-contractions were investigated and respective articles.

Problems including spaces with additional structure (ordered spaces, relational-theoretic spaces, spaces endowed with a graph and spaces with $\alpha$-admissible mappings) were considered in [30, 34, 49, 52, 55, 56, 65, 66, 67, 99, 120, 139, 155].

Spaces with alternate distance or two metrics and respective $F$-contractions were considered in [36, 102].

Vector-valued spaces and Perov-type problems were treated in [21, 90].

$F$-contractions in metric-like and $b$-metric-like spaces were under investigation in [8, 16, 42, 57, 78, 79, 91, 96].

Partial metric spaces and $F$-contractions in them were treated in [17, 100, 114, 133, 134].

Modular and fuzzy-metric spaces and $F$-contractions in them were observed in [10, 11, 59, 64, 87, 104].

Other generalized metric spaces and respective problems were treated in [85, 124, 126, 128]

## 4. Some possibilities for further investigation

We present some open problems for further investigation.

*Question* 4.1. Does an $F$-version hold for Ćirić's quasicontraction (see [43] or [117]), i.e., does the following result hold true: If $(X,d)$ is a complete metric space and if the self-map $T$ on $X$ satisfies

$$\tau + F(d(Tx,Ty)) \leq F(\max\{d(x,y), d(x,Tx), d(y,Ty), d(x,Ty), d(y,Tx)\})$$

for all $x, y \in X$ with $Tx \neq Ty$, where $\tau > 0$ and $F$ satisfies conditions (F1) and (F2), then $T$ has a unique fixed point?

*Question* 4.2. Let $(X,d)$ be a complete metric spaces and let the self-map $T$ on $X$ satisfy

$$\tau + F(d(T^n x, T^n y)) \leq F(d(x,y))$$

for all $x, y \in X$ with $T^n x \neq T^n y$, where $\tau > 0$, $F$ satisfies conditions (F1) and (F2), and $n = n(x,y)$. Does $T$ have a unique fixed point? The positive answer would be a generalization of Sehgal's result [127].

*Question* 4.3. Can conditions for the function $F$ be reduced to (F1) and (F2), and can the proof be made simpler in some results for multivalued mappings in the same way as it was presented in this survey for single-valued mappings?

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Nicola Fabiano
University of Belgrade,
"Vinča" Institute of Nuclear Sciences -
National Institute of the Republic of Serbia,
Mike Petrovića Alasa 12–14,
11351 Belgrade, Serbia
e-mail: `nicola.fabiano@gmail.com`

Zoran Kadelburg
University of Belgrade,
Faculty of Mathematics, Studentski trg 16,
11000 Beograd, Serbia
e-mail: `kadelbur@matf.bg.ac.rs`

Nikola Mirkov
University of Belgrade,
"Vinča" Institute of Nuclear Sciences -
National Institute of the Republic of Serbia,
Mike Petrovića Alasa 12–14,
11351 Belgrade, Serbia
e-mail: `nmirkov@vin.bg.ac.rs`

Vesna Šešum Čavić
University of Belgrade,
Faculty of Civil Engineering,
Bulevar Kralja Aleksandra 73,
11000 Belgrade, Serbia
e-mail: `vsesumcavic@grf.bg.ac.rs`

Stojan Radenović
University of Belgrade,
Faculty of Mechanical Engineering,
Kraljice Marije 16,
11000 Belgrade, Serbia
e-mail: `radens@beotel.net`